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High Energy Neutron Induced Gamma Production

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High Energy Neutron Induced Gamma Production

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N Division has an interest in improving the physics and accuracy of the gamma data it provides to its customers. It was asked to look into major gamma producing reactions for 14 MeV incident neutrons for several low-Z materials and determine whether LLNL's processed data files faithfully represent the current state of experimental and theoretical knowledge for these reactions. To address this, we surveyed the evaluations of the requested materials, made recommendations for the next ENDL release and noted isotopes that will require further experimental study. This process uncovered several major problems in our translation and processing of the ENDF formatted evaluations, most of which have been resolved.

I.   INTRODUCTION

N Division has an interest in improving the physics and accuracy of the gamma data it provides to its customers. Recent testing first by DNT customers and later by the authors revealed serious shortcomings in the gamma data in the recent translated ENDF data release [1]. Figure 1 illustrates these shortcommings with a simple test problem using the ENDF/B-VII.0 and ENDL99 libraries. Here we plot the total energy of gammas escaping from simulations of a mono-isotopic sphere with a 14 MeV neutron source in the center as shown in Figure 2. In general the ENDF/B-VII.0 evaluations are new and *should* have higher quality gamma data than ENDL99, however Figure 1 shows that several of the translated ENDF/B-VII.0 evaluations seem to have no or very few gammas from these 14 MeV neutrons.

In an effort to diagnose the origin(s) of the descrepancies between ENDL99 and ENDF/B-VII.0 gamma data we took a three-pronged approach. One of us (P. Navratil) reviewed the evaluations of several emblematic isotopes
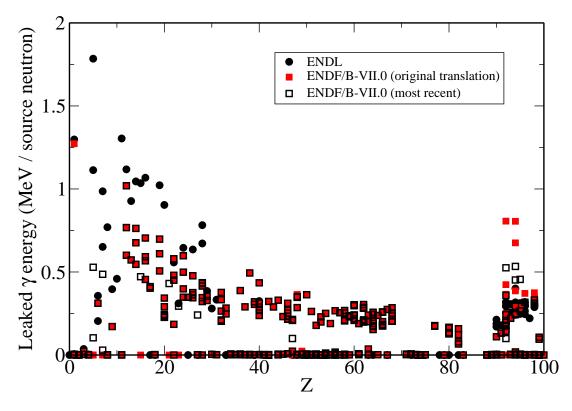

FIG. 1: Mercury calculation of total energy escaping from spheres of various mono-isotopic materials with 14 MeV neutron sources in their centers. Here we use both the ENDL99 library and the original translation of the ENDF/B-VII library. The x axis is the charge of the test isotope, so multiple isotopes are shown with a common Z. The absolute magnitude of the points is not as important as the fact that some points have 0 MeV of emitted γ energy, indicating that there are no γ's being sampled from that particular isotope.
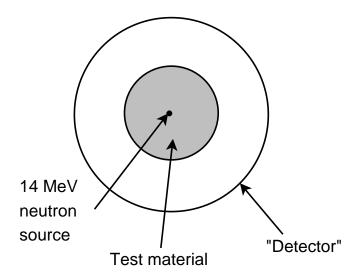
FIG. 2: Cartoon of test system.

Isotope	Recommended action
^{10}B	Start from ENDF/B-VII.0
^{11}B	New data needed
^{12}C	Start from ENDF/B-VII.0
^{14}N	Include new data taken by R. Nelson
^{15}N	Based on calculations, include new data taken by R. Nelson
^{16}O	Use ENDF/B-VII.0
^{19}F	Start from ENDF/B-VII.0
^{27}Al	Start from ENDF/B-VII.0

TABLE I:

(focusing on the high energy gamma production). This also allows us to make several recommendations for changes to the evaluations for later inclusion in the next ENDL library release. Another of us (M. Johnson) reviewed the state of the experimental data on these same isotopes. Finally, the last of us (D. Brown) engaged in a study of all of the steps leading to the production of the processed data files used in our tests.

Below, we will examine the evaluations and measured data for several emblematic isotopes, explain the improvements in our translation and processing of the evaluated data, and provide prospects for improved nuclear theory and experiment for performing the evaluations.

II. GAMMA PRODUCTION FOR DIFFERENT ISOTOPES

We surveyed the neutron induced reaction cross sections relevant for gamma production on stable isotopes ^{10}B, ^{11}B, ^{12}C, ^{14}N, ^{15}N, ^{16}O, ^{19}F and ^{27}Al in the ENDL99 [2], ENDF/B-VII.0 [3], ENDF/B-VI.8 [4], ENDF/B-V [5] and JENDL-3.3 [6] databases. We in particular focused on neutron energy range from 0 to 20 MeV with emphasis on energies around 14 MeV. We assessed the completeness of the data and its accuracy compared to available experimental data. For each isotope, we prepared a PowerPoint presentation with details on relevant neutron-induced nuclear reactions including their threshold energies, Q-values, and cross sections. We identified reactions important for the gamma production. We plotted the cross sections as given in different databases and compared them to each other and to available data. We searched the references describing experiments that produced data used in evaluations. We assessed, which databases are currently most accurate. The PowerPoint presentations can be found as appendixes to this document. A summary of the results is given in Table I.

Experimental data for the above nuclei have also been reviewed for existence, precision, and completeness. For incident neutron energies at 14 MeV, the dominant mode of γ ray production for most of these nuclei is via inelastic neutron scattering. Therefore, we will focus on the (n, n') channel for high-energy γ-ray production.

A. ^{10}B

Gamma rays are dominantly produced in the ^{10}B(n, n') reaction and also in ^{10}B(n, α)^{7}Li*. The ENDF/B-VII.0 evaluation appears to be the most complete and accurate when comared to experimental measurements. We estimate that the ENDF/B-VII.0 gamma production cross sections are accurate within 15%. At 14 MeV, where more experimental data are available, we estimate the accuracy to be about 10%.

Measurement data for the ^{10}B(n, n') channel can be found in Day *et al.* [7] and Cookson *et al.* [8]. These data are used in the ENDF/B-VII.0 evaluations. The former measurement by Day focused on the 718-keV level and will not be discussed further. In the latter measurement by Cookson *et al.*, a quasi-monoenergetic neutrons was generated from a t+p reaction yielding neutrons at 9.7 MeV. Scattered neutrons were measured with scintillators and neutron energies were deduced via TOF. Experimental data for ^{10}B(n,n'γ) at E$_n$= 14 MeV can be found at various places in the literature such as Besotosnyj *et al.* [9]. Uncertainites for this measurement are about 10%.

B. ^{11}B

Gamma rays are produced in the ^{11}B(n, n') reaction and also in ^{11}B(n, α)^{8}Li* reaction. Further, we expect that 0.478 MeV gamma rays should be produced in ^{11}B(n, nα)^{7}Li* reaction as total cross section for this reaction is 300 mb at 14 MeV in ENDF/B-VII.0 evaluation. There are discrepancies among different measurements up to 50%. The ENDF/B-VII.0 evaluation appears to be the most complete. Still, we estimate its uncertainty about 30%.

Cross section data for γ ray production from ^{11}B for the (n, n') channel can be found for the first few excited states (up to 6 MeV) for incident neutron energies up to and including 14 MeV (see Glendenning *et al.* [10]). The measurements were made with scintillators that were set up to trigger on neutrons. The scattered neutron energies were deduced via Time-Of-Flight. The precision of these cross-section measurements is about 5%, an acceptable uncertainty for this measurement. Other measurements of this reaction were made for higher lying states, but the uncertainties are about 30% using a similar detection scheme (see Alder *et al.* [11] and Besotosnyj *et al.* [9]). A recent high precision measurement was made of ^{11}B(n,n'γ) at LANSCE with the latest version of GEANIE (20 HPGes) and is being analyzed by Micah Johnson (co-author).

C. ^{12}C

The gamma rays are produced ^{12}C(n,n') excitation of the first excited state of ^{12}C, the 4.439 MeV 2^+ state. Excitations of higher-lying excited states result in α emission without gamma production. There are several mesaurements of the ^{12}C(n,n'γ) cross section. The ENDF/B-VII.0 and JENDL-3.3 evaluations are in a reasonable agreement. At 14 MeV, the ENDF/B-VII.0 is in a better agreement with most of the measurements. We estimate the ENDF/B-VII.0 accuracy to be 10%.

Results from a ^{12}C(n,n') measurement have been published by Gul *et al.* [12]. Scattered neutrons were detected with scintillators. Due to the large separation and finite number of states, the spectra were relatively clean and reliable. Agreement has been made with a measurement of ^{12}C(n,n'γ) at LANSCE with an early version of GEANIE (5 BGO detectors).

D. ^{14}N

Gamma rays are dominantly produced in the ^{14}N(n, n') reaction and in ^{14}N(n, α)^{11}B* reaction. Other reactions also contribute, for example ^{14}N(n, t)^{12}C*. Many excitation levels of ^{14}N and ^{11}B contribute to gamma production, which makes the measurementrs and evaluations in particular challenging. There are lots of experimental data, yet the evaluations do differ. New data from LANSCE/GEANIE taken by R. O. Nelson at LANL are being analysed [13]. It follows from this private communication that the $8 - 10$ MeV (n, n') data are underestimated in ENDF evaluations while in good agreement at 14 MeV. We therefore recommend to use JENDL-3.3 evaluation for the (n, n') cross sections. The (n, α) cross sections, on the other hand appear to be incomplete in JENDL-3.3, we recommend to use ENDF/B-VII.0 for the (n, α) cross sections as well as for the (n,t) cross sections. We estimate the JENDL-3.3 accuracy for the (n, n') data about 10% at 14 MeV and 20% at lower energies.

E. ^{15}N

The gamma production is dominated by the (n,n') reaction with some contribution from the ^{15}N(n,p)^{15}C* reaction. Experimental cross-section data for ^{15}N(n,n'γ) is non-existent but measurements at LANSCE/GEANIE have been performed and are currently under analysis. There is a significant disagreement between the evaluations and this new data. We recommend to use the new (n,n') and (n,p) data instead of evaluations when the data becomes generally available.

F. ^{16}O

Gamma production is dominated by ^{16}O(n,n') and ^{16}O(n,α)^{13}C* with some contributions from (n,p), (n,d), (n,t) and (n,2n) reactions. A new gamma production experiment was performed at WNR facility at LANL by R. O. Nelson and A. Michaudon [14] using two germanium detectors. The ENDF/B-VII.0 evaluation is based on this measurement. Altogether 23 γ-rays were observed in this measurement. Agreement with some earlier measurements performed in smaller energy windows was achieved. We estimate the accuracy of the experiment and the ENDF/B-VII.0 evaluation to be better than 10%.

G. ^{19}F

Gamma production is dominated by ^{19}F(n,n') and ^{19}F(n,α)^{16}N* with some contributions from (n,p), (n,d), (n,t) and (n,nα) reactions. The ENDF/B-VII.0 evaluation is based mostly on G.L. Morgan and J.K. Dickens ORNL measurement [15]. All evaluations of (n, n') and (n,α) cross sections are in a reasonable agreement. The ^{19}F(n,nα)^{15}N reaction cross section is large and above 10 MeV this reaction may also contribute to the γ production. We recommend to use ENDF/B-VII.0. We estimate its accuracy about 15%.

New measurements of ^{19}F(n,n'γ) have been performed at E$_n$= 14 MeV (see Corcalciuc *et al.* [16], GeLi detectors were used to measure γs). The evaluation only includes the older measurements from ORNL and the details of the experiment or in the ORNL archives. A similar issue exists for ^{27}Al(n,n'γ).

H. ^{27}Al

Gamma production is dominated by ^{27}Al(n,n') with likely contribution from ^{27}Al(n,np)^{26}Si* and also from (n,p), (n,d) and (n,α) reactions. ENDF/B-VII.0 and JENDL-3.3 evaluations are in a reasonable agreement. They are based mostly on the ORNL measurements by Dickens *et al* [17]. The (n,p) and (n,α) cross sections for single levels available only in ENDF/B-VII.0. We note that the (n,np) cross section is quite large. We recommend to use ENDF/B-VII.0. We estimate its accuracy to be about 15%.

III.   LIBRARY TRANSLATION, PROCESSING AND TESTING

In the process of reviewing the evaluations, we noted several problems with the translated data. In particular, we noted that $(n, n\alpha\gamma)$ data was missing from ^{11}B, ^{19}F, and ^{27}Al, all gammas were missing from ^{16}O, and any reaction that had only one gamma associated with the reaction would have no gamma data translated. Resolving these problems led us to completely rewrite of the gamma translation in the `fete` code. It also spurred us to revisit how the gamma data is processed and to introduce some tests of the gamma data. We discuss some of the results of this testing below.

A.   Library translation

Translating the ENDF files into ENDL format is a complicated process handled by the ENDF to ENDL translation code `fete`. Until recently, `fete` consisted of an ad-hoc collection of routines for translating the various forms in ENDF that gamma data are stored. These formats include MF = 12 and 13 files for the multiplicities (MF = 13 is the production cross-section), MF = 14 files for the angular distributions and MF = 15 files for the energy spectrum of continuum gammas. There are also gammas in the MF = 6 files containing correlated energy-angle distributions, but

as this code was written very recently, we did not need to revisit it. In ENDF, the multiplicity and discrete gamma energy can also be stored as a table of branching ratios for the (n, n') gammas. With these files, `fete` proceeds systematically through all of the files associated with a reaction, translating each one in turn without regard for whether each file was properly synchronized with the others associated with this reaction.

In this rewrite of `fete`'s gamma translation, we attempted to be more object-oriented. Rather than attempting to translate one MF at a time, we now collect all of the data corresponding to a single gamma into one data structure deriving from the `Gamma` base class. This class contains references to a gamma's multiplicity, energy distribution (derived from MF=12, 13 and 15 files) and angular distribution (derived from MF=14 files). The `Gamma` class is sub-classed to handle some special cases, namely `DiscreteGamma` (and its derived classes `PrimaryDiscreteGamma` and `SecondaryDiscreteGamma`), `ContinuumGamma` and `AccumulatorGamma`. The `AccumulatorGamma` is a special class that allows us to sum up individual gammas of any type into one "monster" gamma suitable for output in ENDL format. The `Gamma` instances are held in a C++ `stl::vector`, allowing us to rearrange where gammas are to be output. This vastly simplifies the coding for the C=55 gamma data.

We verified the fidelity of the translated data by hand for a few cases:

^{nat}C: Has few lines, with small mix of primary and secondary discrete gammas.

^{16}O: Has many lines; some reactions have all isotropic angular dists while others have a mix of Legendre order data and isotropic distributions.

^{15}N: Uses MF=15 for continuum gammas.

^{24}Mg: Uses a gamma cascade for the (n, n') gammas.

After the translation has completed, we run the `fudge` scripts detailed in [1] to repair the translated data. In the cases of interest in the previous section, there were some fixes we needed to apply by hand. In the ^{nat}C evaluation, the breakup flag is used incorrectly leading to the C=27 $(n, n2\alpha)$ being stored as C=36 $(n, n3\alpha)$. In addition, this evaluation has correlated $E - \mu$ data stored in MF=4, MT=51-90 files, abusing the break-up reaction data format. In the ^{14}N evaluation, the (n, γ) gamma data is misfiled with the elastic data.

B. Processing

The first step in processing the data libraries is the calculation of the energy depositions. We use the most recent incarnation of `endep` called `endepC++`. The energy depositions are still computed in the original fashion with the exception of the C=55 gamma energy deposisions. Often an evaluation is a patchwork of older evaluations which can wreck the energy balance in a particular reaction channel. This is especially true if the gammas for a particular reaction were originally contained in the C=55 file, but the evaluator associates some with a particular reaction, resulting in a double counting. To counter this, `endepC++` can reduce the C=55 gamma multiplicity so that the C=55 gammas do not exceed the maximum available energy available to all channels.

With this, the data is packaged either for deterministic calculations (using `ndfgen` for input to `libndf`) or Monte-Carlo calculations (using `mcfgen` for `mcapm`). In either case, we have not updated any of the codes to handle the translated data.

C. Testing

To test the processed data libraries, we developed the simple sanity test mentioned in the introduction. In it, we measure the gamma leakage from a 14 MeV neutron source in a sphere of a specific isotope (as shown in Figure 2). Figure 1 shows the results before and after the gamma translation rewrite. We deam the test sucessful on a particular isotope if gammas are produced. In Figure 1 we note a couple of important things. First, the leakage in some actinides actually decreased over the length of this project. In the original translation, there was too much C=55 energy and this bug has now been fixed. Second, we note that the majority of isotopes actually are done properly, they just do not have that many gammas. This can be seen in the log plot in Figure 3. Finally, we note that real improvements only occured in Z¡20 where many isotopes are now being translated properly.

Sadly, we have found several isotopes that, when gamma tracking is turned on, crash Mercury. The current list of failed isotopes include ^{1}H, ^{16}O, and several other important isotopes. The complete list if given in Table II. We suspect that these are processing or software library problems as we verified the translated data by hand for ^{16}O and ^{23}Na.
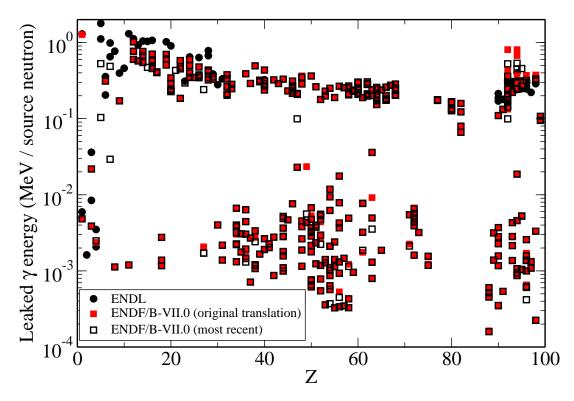
FIG. 3: This is the same figure as Figure 1, but plotted on a logrithmic scale to emphasis the low number of gammas leaked from many isotopes.

za001001	za042092	za073181	za083209
za008016	za042094	za074000	za096242
za011023	za042096	za074182	za099120
za022047	za042097	za074183	za099125
za028059	za042098	za074184	za099253
za041093	za050125	za074186	za099254
	za067165	za079197	za099255

TABLE II: List of isotopes that failed our gamma sanity check, resulting in crashes of Mercury.

IV. FUTURE OUTLOOK

A. Theoretical Outlook

We found that present evaluations rely on the same physical models and tools used for neutron cross section evaluations on medium and heavy nuclei. These models include the optical model calculations and fits, the Hauser-Feshbach statistical model approach to compound nucleus reactions with corrections from preequilibrium theory. The tools include the Gnash system of statistical model codes, the Dwuck direct reaction code, the Sammy R-matrix code, the TNG statistical and precompound theory code and also the Sincros-II code system used by the JENDL-3.3 evaluators. It should be mentioned that these approaches may not be quite appropriate for the lighter nuclei surveyed. This is due to the fact that the level densities in light nuclei are much lower than in medium and heavy nuclei. Consequently, the assumptions on which the statistical approach and compound nucleus formation are based are not quite met in these light nuclei. Further, the direct contribution was obtained using optical model approach without performing coupled-channel calculations. In light nuclei, exitations of low-lying states, most of which are important for the gamma production, proceed by fast direct processes that are best described within the direct reaction coupled channel formalism. Another prominent feature in the structure of light nuclei is clustering, in particular alpha clustering. A consequence of that is the importance of resonances. A description of cross sections with resonances due to clustering is impossible within the statistical model. A proper treatment of nuclear structure

is therefore important for an accurate description of nuclear reactions on light nuclei.

We are currently developing an *ab initio* theory of nuclear structure and reactions applicable to light nuclei. This theory will provide a new capability that will improve the theory component of nuclear data evaluations. First, coupled channel calculations can be performed for the (n,n') reactions conveniently using optical potentials from a folding approach and *ab initio* transition densities. We have the capability to calculate one-body transition densities within the *ab initio* no-core shell model approach for light nuclei with $A \leq 16$ and even beyond. These transition densities can then be utilized to perform folding calculations within the JLM theory. The result of these calculations are optical potentials suitable for coupled channel calculations that can be performed using the coupled-channel reaction code FRESCO. We have all the codes working and the whole scheme was tested for the n+^{11}B inelastic scattering.

A significant improvement over this combined *ab initio*-phenomenological approach is a new method we are working on. Presently, we are developing an *ab initio* approach to nuclear reactions based on the resonating group method (RGM). The first applications to the (n,n') reactions are within the reach. The major feature is microscopic coupling of the direct and resonant processes. As this theory is further developed, we will perform microscopic RGM-type calculations that will include not only the direct contributions but also the resonance contributions and also coupling to channels with different outgoing clusters (in addition to (n,n')).

Finally, we note that in many cases the evaluations lack gamma data from the (n, n') discrete level excitation reactions. In this case, mcapm manufactures a fictional γ ray from a state excited to the ground state instead of a γ ray cascade that proceeds through several lower-lying excited states. A straightforward improvement can be implemented immediately: the use of proper branching ratio to generate the γ ray cascades. For levels with experimentally unknown branching ratios, the branching ratios obtained within the *ab initio* nuclear structure calculations can be supplied.

B. Experimental Outlook

No further action from the experimental side is needed for most of the nuclei reviewed here. A recent measurement of ^{11}B(n,n'γ) is being analyzed by Micah Johnson to produce higher precision cross-section data for high excitations. ^{14,15}N(n,n'γ) measurements have been performed and are under analysis by researchers at LANSCE.

C. Processing and Testing Outlook

This exercise serves again to emphasise the importance of data testing. We are now working to resolve all problem isotopes listed in Table II. In addition, we are developing other tests including reflected critical assemblies and mock-ups of the pulsed sphere tests performed at LLNL.

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$^{10}\text{B}(n,X\gamma)$

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n+^{10}B reactions for $E_n \leq 20$ MeV
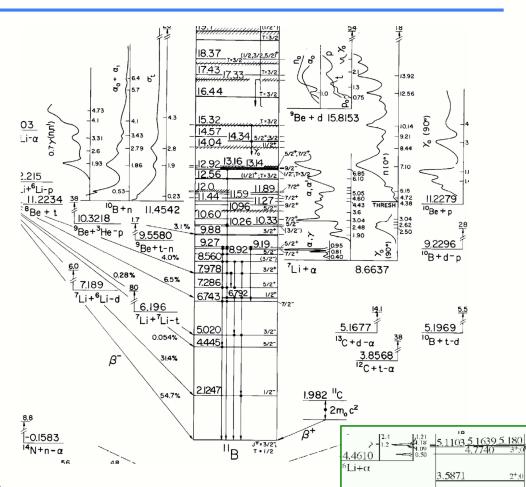
Reaction	Q value [MeV]	Threshold Energy [MeV]
^{10}B(n,γ)^{11}B	+11.4542	0
^{10}B(n,α)^{7}Li	+2.7905	0
^{10}B(n,α)^{7}Li*	+2.3129	0
^{10}B(n,t)^{8}Be	+0.2308	0
^{10}B(n,p)^{10}Be	+0.2263	0
^{10}B(n,n)^{10}B	0	0
^{10}B(n,n')^{10}B*	-0.7184	0.7907
^{10}B(n,p)^{10}Be*	-3.1417	3.4583
^{10}B(n,nα)^{6}Li	-4.4610	4.91
^{10}B(n,d)^{9}Be	-4.3613	4.8007
^{10}B(n,nd)^{8}Be	-6.0267	6.63
^{10}B(n,np)^{9}Be	-6.5859	7.24
^{10}B(n,nα)^{6}Li*	-6.647	7.31
^{10}B(n,2n)^{9}B	-8.4363	9.2861
^{10}B(n,^{3}He)^{8}Li	-15.755	17.33
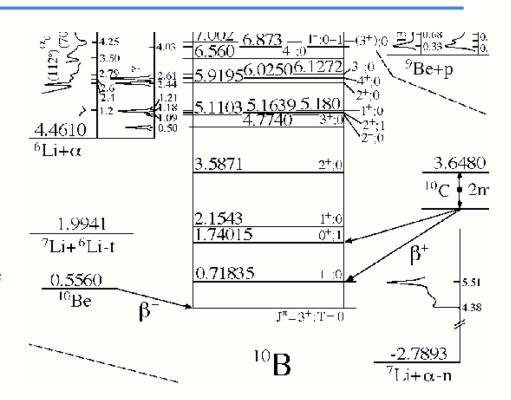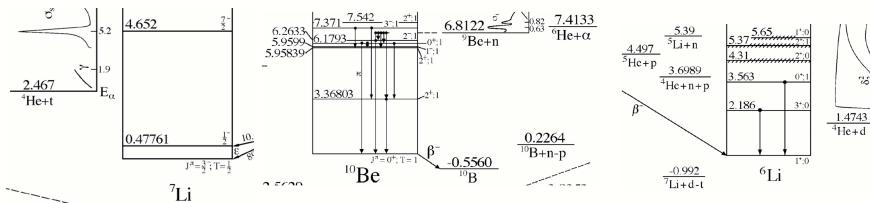
- ^{10}B abundance 19.8% (^{11}B 80.2%)
- γ production from ^{10}B(n,n')^{10}B*
- Significant contribution from ^{10}B(n,α)^{7}Li*
- ^{10}B(n,γ)^{11}B negligible: $\sigma_{(n,γ)}$(14 MeV)≈0

γ production by n+^{10}B

- ^{10}B(n,n')^{10}B*
  - Levels up to E_x=6.03 MeV contribute
- ^{10}B(n,α)^{7}Li*
  - The E_x=0.4776 MeV level contributes
- ^{10}B(n,p)^{10}Be*
  - Levels up to E_x=6.2 MeV contribute
- ^{10}B(n,nα)^{6}Li*
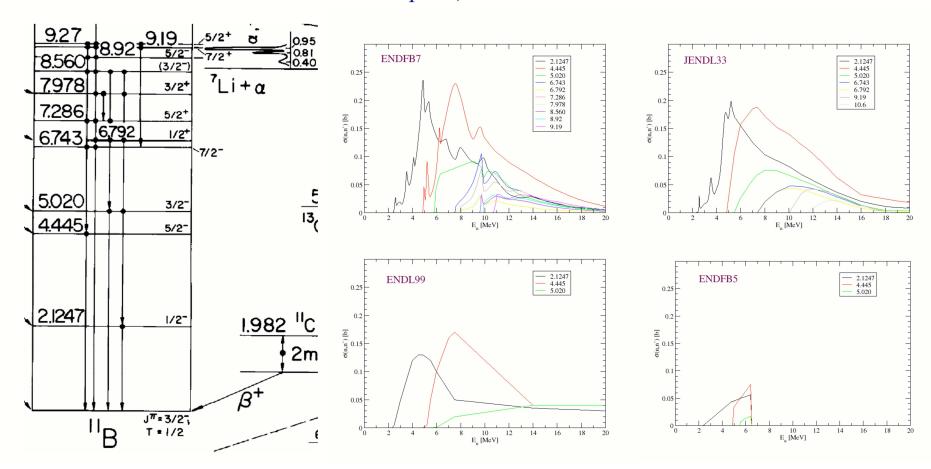 - Levels up to E_x=3.6 MeV may contribute
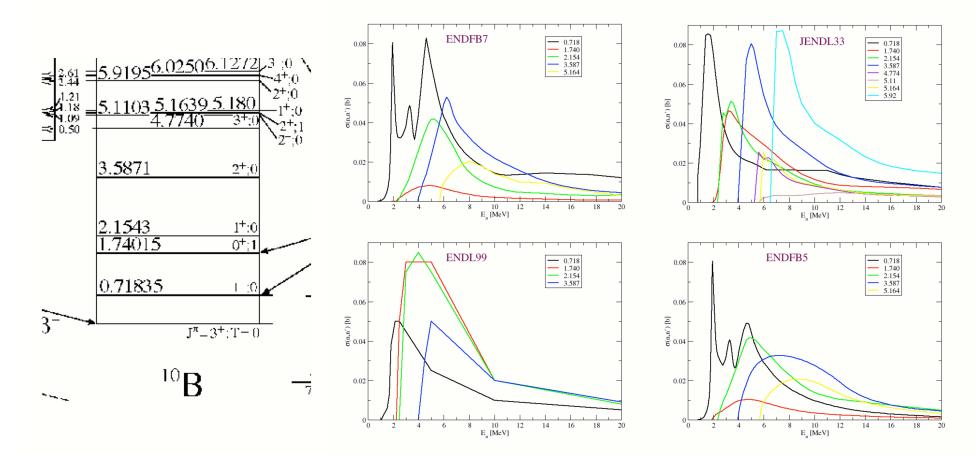
$^{10}B(n,n')^{10}B^*$

- (n,n') cross section dominated by 0.718 MeV 1^+ and 3.587 MeV 2^+ levels
- Big differences between ENDFB7 and JENDL33
  - Measurement at 9.72 MeV by Cookson *et al.*, NP**A146**, 417 (1970):
    - 16 mb for (1.74+2.15); 32 mb for 3.59; 33 mb for (5.2); 116 mb for (5.92+6.03+6.13)

^{10}B(n,n')^{10}B*(0.718)
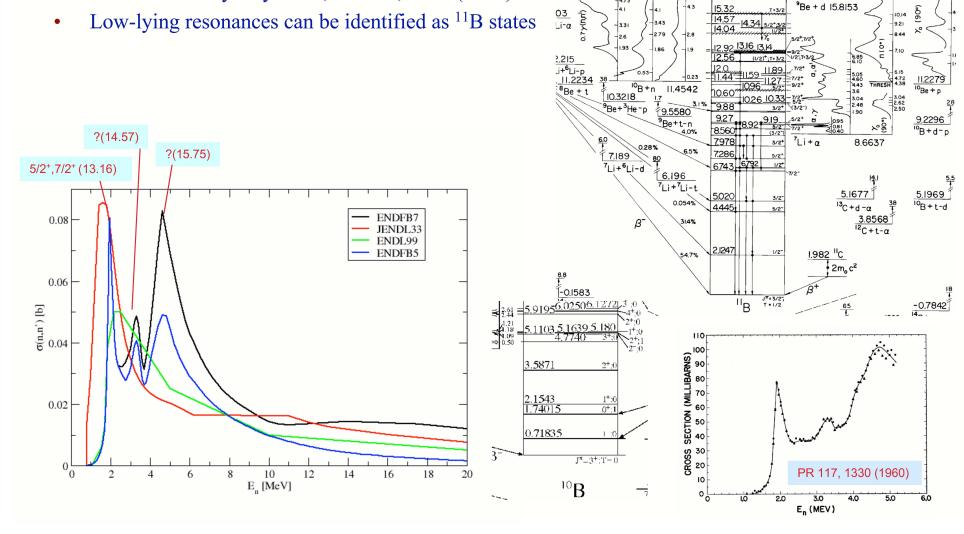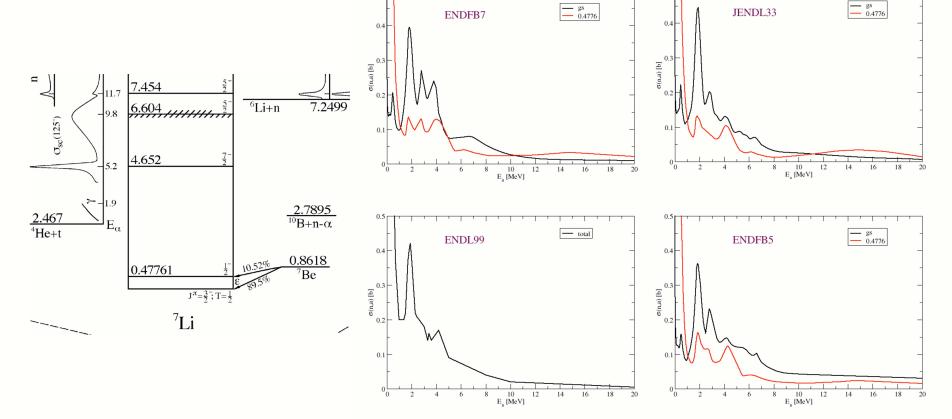
- Measurement by Day *at al*., PR 117, 1330 (1960)
- Low-lying resonances can be identified as ^{11}B states

5/2$^+$,7/2$^+$ (13.16)

?(14.57)

?(15.75)

PR 117, 1330 (1960)

^{10}B(n,α)^{7}Li
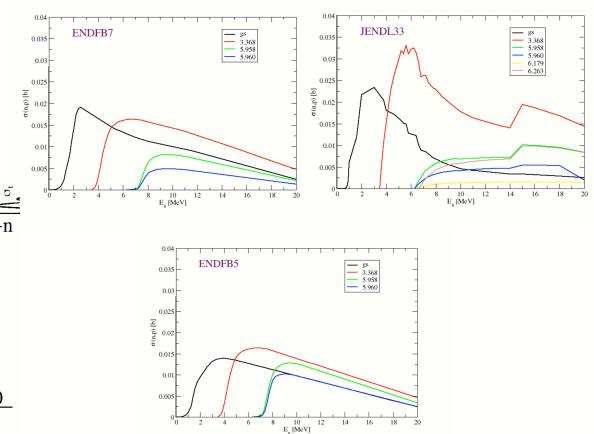
- **Measurement by Nellis *et al.*, PRC 1, 847 (1970): 0.4776 γ-ray production at 14.8 MeV σ=34±3 mb**
- **At 14 MeV**
    - ENDFB7: 33 mb
    - JENDL33: 33 mb
    - ENDL99: <20 mb (total)
    - ENDFB5: 23 mb
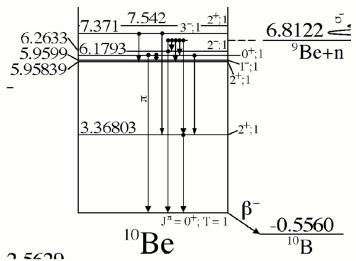
^{10}B(n,p)^{10}Be

- 2.6 MeV ($1^- \rightarrow 2^+$) and 3.37 MeV transitions seen by Nellis *et al.*, PRC **1**, 847 (1970)
- Cross sections very small
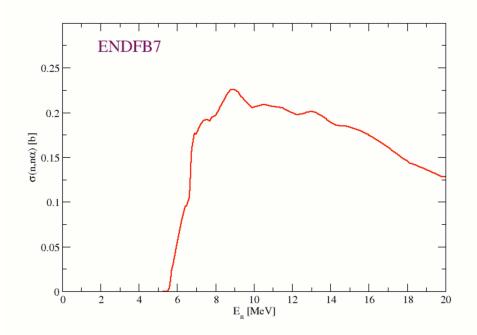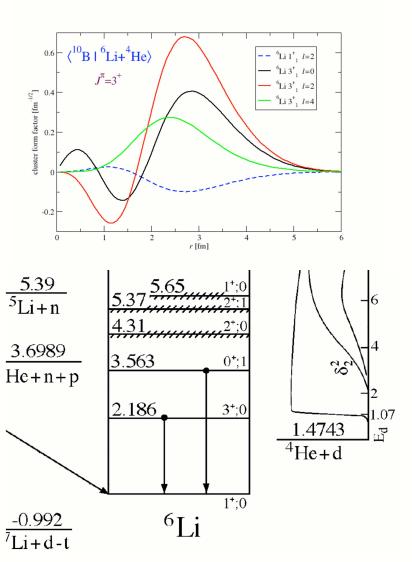
$^{10}B(n,n\alpha)^6Li$
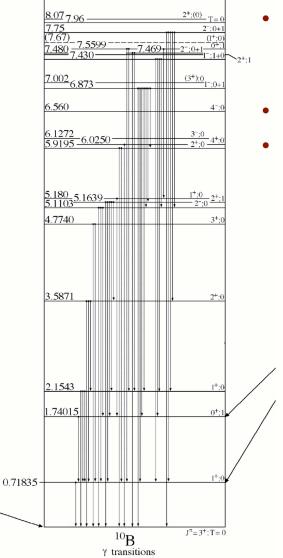
- ## Very large cross section
  - For $E_n > 12$ MeV bigger than the (n,n')
  - Likely no gamma rays
    - 2.18 MeV: $\Gamma_\alpha = 24$ keV, $\Gamma_\gamma = 4 \times 10^{-4}$ eV
    - 3.563 MeV: $\Gamma_\gamma = 8.2$ eV; T=1
      - Possibility mentioned by Nellis
      - Obscured by 3.59 MeV in ^{10}B

$\langle ^{10}B \mid {}^6Li + {}^4He \rangle$

$J^\pi = 3^+$
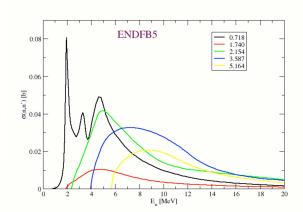
ENDFB7

^{10}B(n,Xγ)
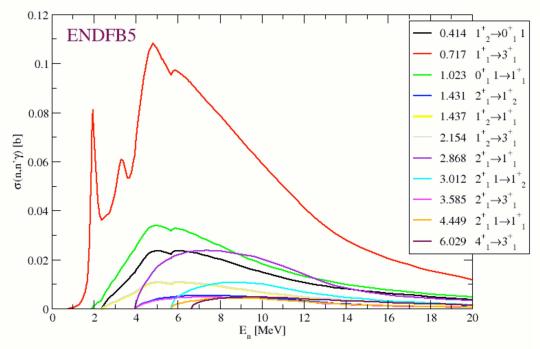
- **Only ENDFB5 contains gamma production cross sections**
- **Gamma rays from (n,n') only**
- **Dominated by 0.718 MeV**

^{11}B(n,Xγ) evaluations

- **All databases contain**
  - (n,n') cross section files yo00c11i000s001
  - Cross sections files yo00cxyi000s000 with xy=46(n, γ)
- **ENDL99 also contains**
  - Cross section files yo00cxyi000s000 with xy=11(n,n'), 23(n,ndα), 31(n,2npα), 43(n,dn), 45(n,α)
- **ENDEFB7 also contains**
  - Cross section files yo00cxyi000s000 with xy= 20(n,np), 26(n,nα), 40(n,p), 41(n,d), 42(n,t), 45(n,α)
  - yo00cxyi000s001 with xy= 40(n,p), 45(n,α)
- **ENDFB5 also contains**
  - Cross section files yo00cxyi000s000 with xy= 41(n,d), 43(n,dn)
  - yo00cxyi000s001 with xy=20(n,np), 23(n,ndα), 26 (n,nα), 40(n,p), 45(n,α)
  - yo00c55i000s003: (n,Xγ); X=n' only
- **JENDL33 also contains**
  - yo00cxyi000s000 with xy=12(n,2n), 40(n,p), 41(n,d), 42(n,t), 45(n,α)
  - yo00cxyi000s001 with xy=40(n,p), 41(n,d), 45(n,α)

Conclusions

- Not that many experimental data
- Different evaluations contain different data files
- ENDFB7 modifies ENDFB6 below 1 MeV
- ENDFB6 improves on ENDFB5
    - New data, new analysis, reconciliation of (n,n') and gamma ray data
- ENDL99 rather schematic, appears not to include 1970 data
- JENDL33 relies more on calculations than ENDFB7
- Presently, the ENDFB7 appears the most solid

$^{11}\text{B}(n,X\gamma)$
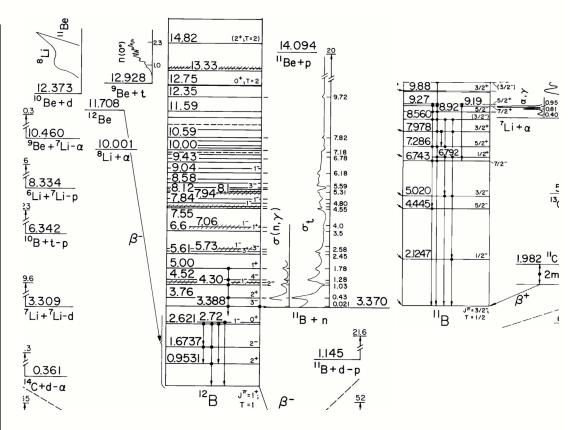
Petr Navratil

Lawrence Livermore National Laboratory*

30 March, 2007

n+^{11}B reactions for $E_n \leq 20$ MeV

Reaction	Q value [MeV]	Threshold Energy [MeV]
^{11}B(n,γ)^{12}B	+3.370	0
^{11}B(n,n)^{11}B	0	0
^{11}B(n,n')^{11}B*	-2.1247	2.3194
^{11}B(n,α)^{8}Li	-6.631	7.23
^{11}B(n,α)^{8}Li*	-7.6118	8.30
^{11}B(n,nα)^{7}Li	-8.6637	9.459
^{11}B(n,d)^{10}Be	-9.003	9.830
^{11}B(n,nα)^{7}Li*	-9.1413	9.97
^{11}B(n,t)^{9}Be	-9.558	10.434
^{11}B(n,p)^{11}Be	-10.724	11.706
^{11}B(n,p)^{11}Be*	-11.044	12.05
^{11}B(n,n2α)^{3}H	-11.1316	12.152
^{11}B(n,nt)^{8}Be	-11.2234	12.24
^{11}B(n,np)^{10}Be	-11.2279	12.257
^{11}B(n,2n)^{10}B	-11.4542	12.504
^{11}B(n,2n)^{10}B*	-12.1726	13.28
^{11}B(n,d)^{10}Be*	-12.371	13.50
^{11}B(n,np)^{10}Be*	-14.596	15.92
^{11}B(n,nd)^{9}Be	-15.8153	17.25
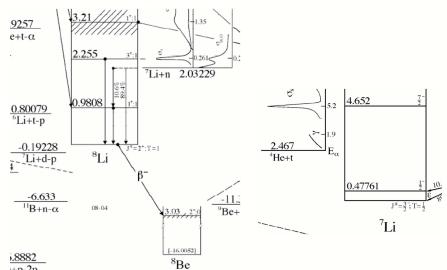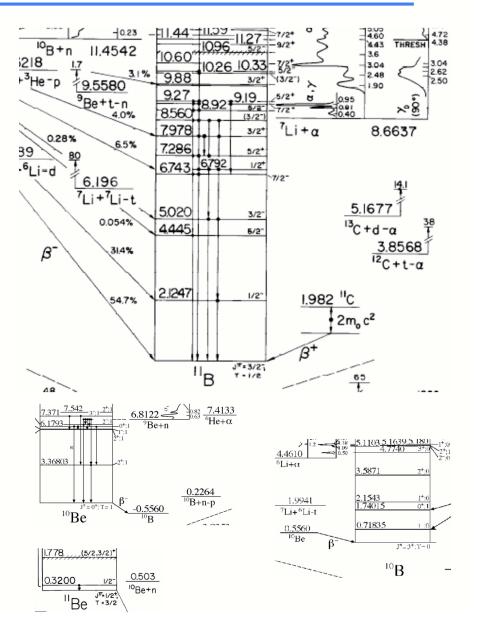
- ^{11}B abundance 80.2% (^{10}B 19.8%)
- γ production dominated by ^{11}B(n,n')^{11}B*
  - Some contribution from ^{11}B(n,α)^{8}Li*
  - Contribution from ^{11}B(n,nα)^{7}Li* likely
- ^{11}B(n,γ)^{12}B negligible: $\sigma_{(n,\gamma)}$(14 MeV)$\approx$10^{-7} b

γ production by n+^{11}B

- ^{11}B(n,n')^{11}B*
  - Levels up to E_x=8.56 MeV contribute
- ^{11}B(n,α)^{8}Li*
  - The E_x=0.9808 MeV level contributes
- ^{11}B(n,nα)^{7}Li*
  - The E_x=0.4776 MeV level should contribute
- ^{11}B(n,d)^{10}Be*
  - Levels up to E_x=6.2 MeV may contribute
- ^{11}B(n,2n)^{10}B*
  - Levels up to E_x=3.6 MeV may contribute
- ^{11}B(n,p)^{11}Be
  - The E_x=0.32 MeV level may contribute

$^{11}B(n,n')^{11}B*$
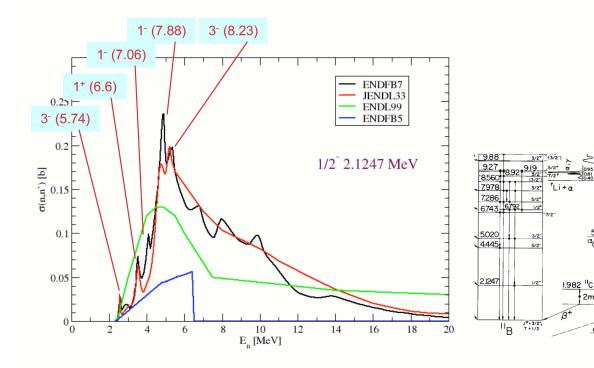
- (n,n') cross section dominated by 2.1247 MeV $1/2^-$ and 4.445 MeV $5/2^-$ levels
- Some differences between ENDFB7 and JENDL33
  - More resonant structure in ENDFB7
- ENDL99 and ENDFB5 incomplete, schematic
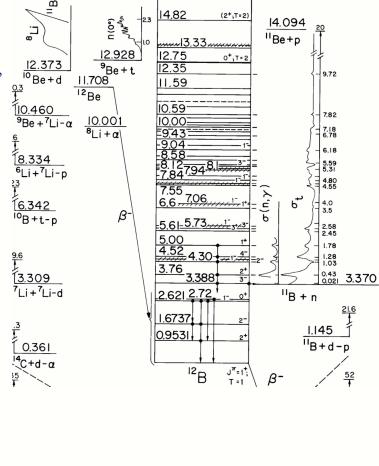
^{11}B(n,n')^{11}B*(2.1247)

- ENDFB7 follows 8-14 MeV data by S. G. Glendinning *et al.*, NSE **80**, 256 (1982) and P.E. Koehler et al., NP**A394**, 221 (1983)

- ENDL99 uses the 7.55 MeV measurement by Hopkins and Drake, NSE **36**, 275 (1969): 52(16) mb (Koehler: 100(2) mb)

- ENDFB5: data above 6.4 MeV in s000 file

- ENDL99 and ENDFB5: error in E_x: 2.14 vs. 2.1247

- Resonances can be identified as ^{12}B states
  - Some are seen in the total cross section as well
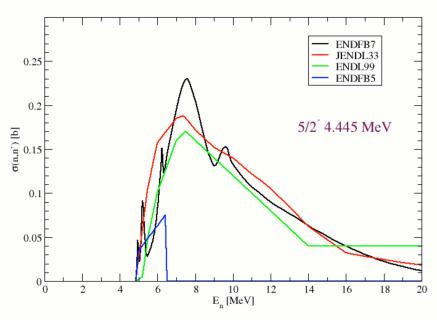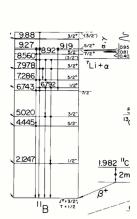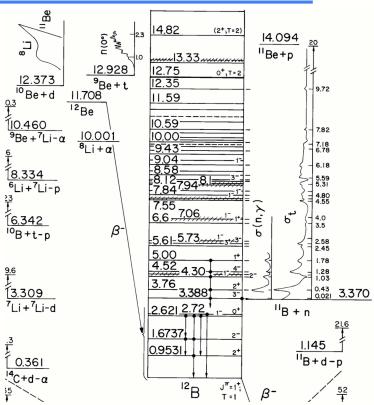
$^{11}B(n,n')^{11}B^*(4.445)$

- ENDFB7 follows 8-14 MeV data by S. G. Glendinning *et al.*, NSE **80**, 256 (1982) and P.E. Koehler et al., NP**A394**, 221 (1983)
- JENDL33 references the above but smoothes the data
- ENDL99 uses the 7.55 MeV measurement by Hopkins and Drake, NSE **36**, 275 (1969): 168(25) mb
  - Koehler at 7.55 MeV: 218(5) mb
- ENDL99 and ENDFB5: error in E_x: 4.458 vs. 4.445

5/2⁻ 4.445 MeV
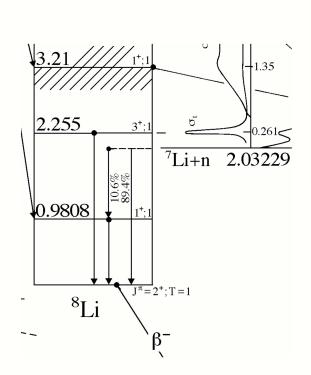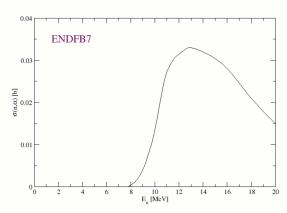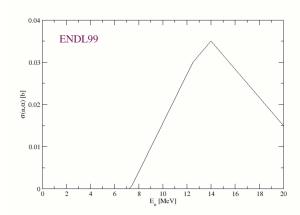
$^{11}B(n,\alpha)^8Li$
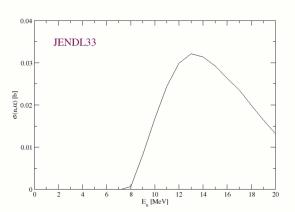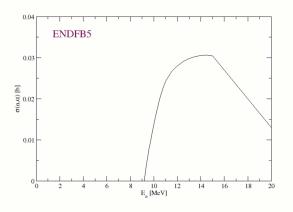
- **Measurements by Armstrong and Frye, PR 103, 335 (1956)**
  - E_n from 12.6 to 20 MeV
  - Sum of $^8Li_{gs}$ and $^8Li_{1+}$
- **Measurement by Antolkovic and Rupnik, NPA325, 189 (1979)**
  - E_n=14.4 MeV
  - Separate gs (20.5(35) mb) and 1^+ (10.9(25) mb)
- **Value at 14 MeV well established**
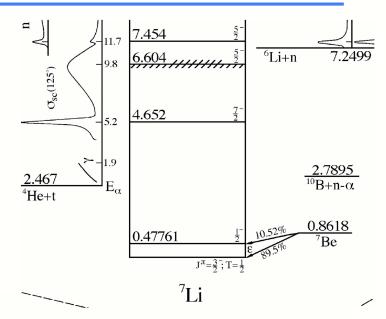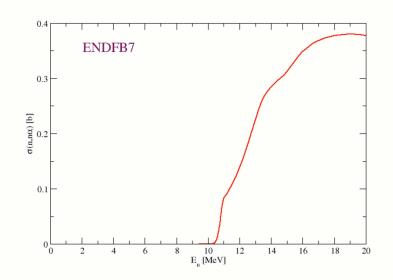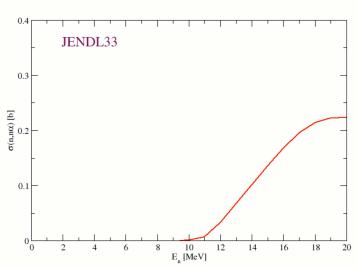
$^{11}B(n,n\alpha)^7Li$

- **Very large cross section**
  - For $E_n > 12$ MeV bigger than the (n,n')
  - Must produce 0.478 gamma ray
- **No data in ENDL99 and ENDFB5 at all**
- **No gamma data in either database**

^{11}B(n,Xγ) evaluations

- **All databases contain**
  - (n,n') cross section files yo00c11i000s001 and yo00c11i000s000
  - Cross sections files yo00cxyi000s000 with xy=12(n,2n),45(n,α),46(n, γ)
- **ENDL99 also contains**
  - Cross section files yo00cxyi000s000 with xy=40 (n,p)
  - Cross section file yo00c42i000s001 (n,t): only gs data, however
- **ENDEFB7 also contains**
  - Cross section files yo00cxyi000s000 with xy= 20(n,np),26(n,nα),40(n,p),42(n,t)
- **ENDFB5 also contains**
  - Cross section files yo00cxyi000s000 with xy=42(n,t),55
  - yo00c55i000s000: (n,Xγ): energy 20 MeV and value 0
- **JENDL33 also contains**
  - yo00cxyi000s000 with xy=20(n,np),22(n,nd),24(n,nt),26(n,nα),27(n,nα),40(n,p),42(n,t)
  - yo00c55i000s000 (n,Xγ)

Conclusions

- Not that many experimental data
- Large discrepancies among experimental measurements of (n,n') cross sections
- Different sets of cross sections in different evaluations
- ENDFB7 and JENDL33 independent evaluations/calculations
  - JENDL33 uses Gnash code, DWBA, R-matrix
  - Data references similar for ENDFB7 and JENDL33
  - ENDFB7 also includes private communication as experimental data reference
- ENDFB7 identical to ENDFB6
- ENDFB5 appears incomplete
- ENDL99 relies on old data
- No gamma cross section files ((n,nα)^{7}Li*???)
- New data likely needed
- Presently, the ENDFB7 appears the most solid

^{12}C(n,Xγ)
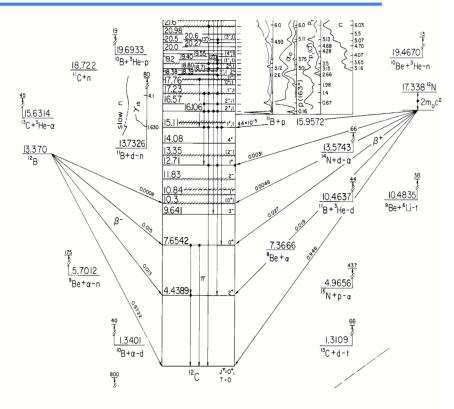
Petr Navratil

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22 December, 2006

n+^{12}C reactions for $E_n \le 20$ MeV

Reaction	Q value [MeV]	Threshold Energy [MeV]
^{12}C(n,γ)^{13}C	+4.947	0
^{12}C(n,n)^{12}C	0	0
^{12}C(n,n')^{12}C	-4.439	4.812
^{12}C(n,α)^{9}Be	-5.702	6.181
^{12}C(n, n'3α)	-7.275	7.887
^{12}C(n,p)^{12}B	-12.588	13.646
^{12}C(n,d)^{11}B	-13.733	14.888
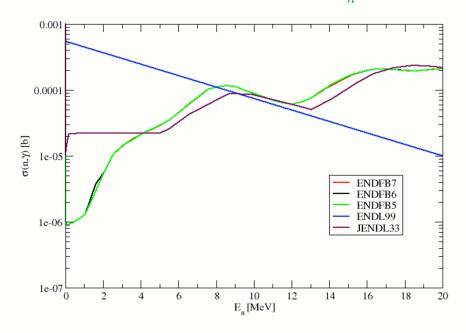
- States above the 3α threshold up to $E_x \approx 15$ MeV decay into 3α
  - Dominated by a sequential decay through ^{12}C(n,α)^{9}Be*(2.43)(2α) at low E_n and by ^{12}C(n,n')^{12}C*(9.63)^{8}Be$_{g.s.}$(2α) at higher E_n
- γ production through ^{12}C(n,γ)^{13}C for $E_n \le 4.812$ MeV
  - Small cross section
- γ production completely dominated by ^{12}C(n,n')^{12}C*(4.439)

γ production by n+^{12}C
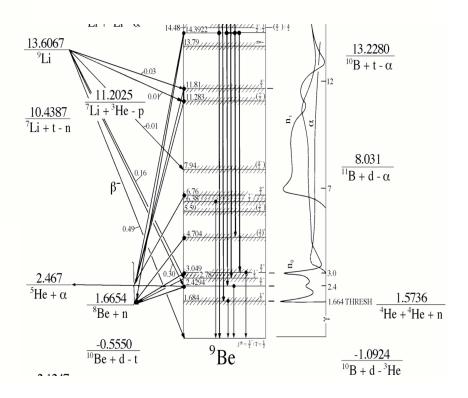
- ^{12}C(n,γ)^{13}C
  - Cross section 2×10^{-4} b at $E_n = 14$ MeV

- ^{12}C(n,α)^{9}Be*
  - ^{9}Be excited states decay by n and/or α emission
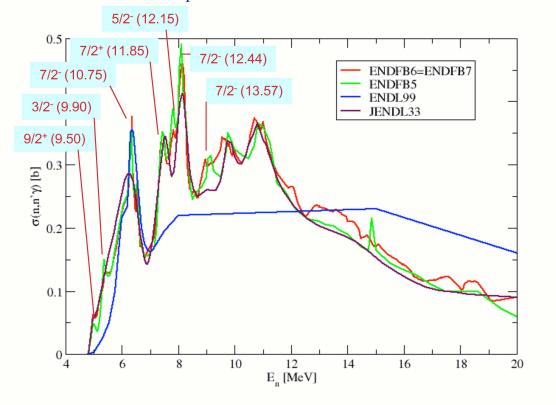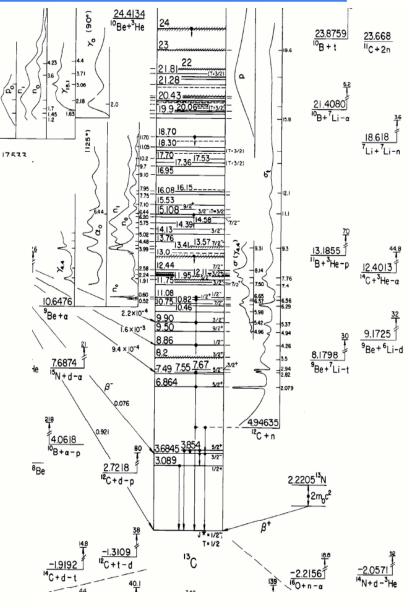
^{12}C(n,n')^{12}C*(4.439)

- F. Ajzenberg-Selove, Nucl. Phys. **A523** (1991) 1
- Data evaluations
  - JENDL33
  - ENDL99
  - ENDFB5
  - ENDFB6 & ENDFB7
- Peaks correspond to ^{13}C resonances

$^{12}C(n,n')^{12}C^*(4.439)$ evaluations

- **All databases contain**
  - the cross section file yo00c11i000s001
  - Neutron angular probability distribution file yo01c11i001
- **ENDFB5 contains**
  - Energy-angle probability distribution file yo07c11i004s001
  - Photon multiplicity yo07c11i009s001 and average energy deposit yo07c11i010s001 files
- **ENDL99 contains**
  - yo00c55i000s003 identical to yo00c11i000s001
  - Average energy deposit file yo07c11i010s001
    - Identical yo07c55i010s003
  - Photon angular probability distribution file yo07c55i001s003

ENDFB7 ^{12}C(n,n')^{12}C*(4.439) evaluation

- 4.81 MeV-6.32 MeV

  - σ_{tot}- σ_{el}- $\sigma_{(n,\gamma)}$

    - based on measurements; $\sigma_{(n,\gamma)}$ derived from $\sigma_{(\gamma,n)}$

- 6.32 MeV-8.796 MeV

  - σ_{tot}- σ_{el}- $\sigma_{(n,\gamma)}$ - $\sigma_{(n,\alpha)}$

- 8.796 MeV-32 MeV

  - Measurements:

    - D.E. Velkley et al., PRC **7**, 1736 (1973);
    - G. Haouat et al. NSE 65, 331 (1978);
    - K. Gul et al., PRC **24**, 2458 (1981);
    - G.L. Morgan et al,ORNL-TM-3702 (1972).

- A measurement consistent with

  J.K. Dickens, G.L. Morgan et al.
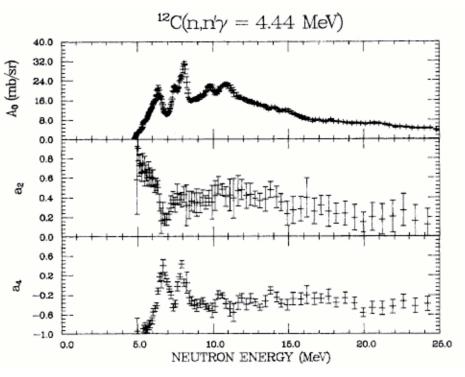
  reported by S.A. Wender et al,

  Inst. Phys. Conf. Ser. No. 88/J.Phys. G:

  Nucl.Phys. 14 Suppl.

  White neutron source at LAMPF

  γ-ray excitation function and angular distribution

JENDL33 $^{12}C(n,n')^{12}C^*(4.439)$ evaluations
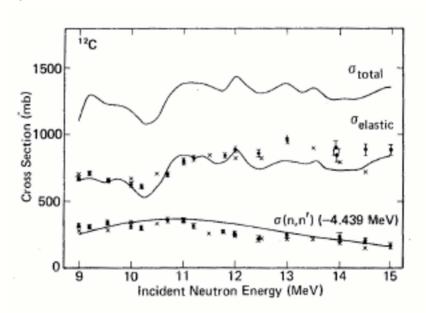
- **Based on measurements:**
  - G.L. Morgan et al., ORNL-TM-3702 (1972).
  - G. Haouat et al. NSE **65**, 331 (1978).
  - D.W. Glasgow et al., NSE **61**, 521 (1976).
  - V.C. Rogers et al., DNA 3495F (1974).

- **Figure from D.W. Glasgow et al.:**
  - Scattered neutron differential
    cross section measured

$^{12}C(n,n')^{12}C^*(4.439)$ for E_n=14 MeV

- K. Gul et al., PRC **24**, 2458 (1981):

TABLE II. Summary of the measured integrated scattering cross sections of the various states of ^{12}C and their comparison with the published data.

	Present	Haouat et al. (Ref. 7)	Glasgow et al. (Ref. 8)	Bouchez et al. (Ref. 2)	Grin et al. (Ref. 6)	Clark Cross
Ground state	830 ± 15^a	730	887 ± 52	810 ± 40	775 ± 35	730 ± 70
4.43 MeV	214 ± 8	146.4 ± 8	202 ± 8.8	215 ± 40	215 ± 15	209 ± 20
7.65 MeV	9.3 ± 1.6			16 ± 10	8.5 ± 2	

[a]Average value of the elastic scattering cross-section computed from the optical model parameters containing in Table I.

- Evaluations
  - ENDFB7 & ENDFB6: 210.6 mb
  - ENDFB5:   190   mb
  - ENDL99:   230   mb
  - JENDL33:   183   mb

- LLNL measurement by E. Goldberg et al., NSE **105**, 319 (1990):
  - Slightly better agreement with data found for the ENDL99 rather than ENDBF5
    - 190 mb likely too low

Conclusions

- The ENDFB7 evaluation appears to be the best
- ENDL99 incomplete, old
  - The 14 MeV cross section reasonable, likely slightly higher than reality
- JENDL33 evaluation does not have all the resonances
  - The 14 MeV cross section too low

^{14}N(n,Xγ)

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Lawrence Livermore National Laboratory*

2 March, 2007

n+^{14}N reactions for $E_n \leq 20$ MeV

Reaction	Q value [MeV]	Threshold Energy [MeV]
^{14}N(n,γ)^{15}N	+10.8333	0
^{14}N(n, p)^{14}C	+0.6259	0
^{14}N(n,n)^{14}N	0	0
^{14}N(n,α)^{11}B	-0.1581	0.170
^{14}N(n,α)^{11}B*	-2.2828	2.447
^{14}N(n,n')^{14}N*	-2.3128	2.479
^{14}N(n,t)^{12}C	-4.0151	4.304
^{14}N(n,d)^{13}C	-5.326	5.710
^{14}N(n, p)^{14}C*	-5.4679	5.862
^{14}N(n, np)^{13}C	-7.5506	8.09
^{14}N(n,d)^{13}C*	-8.415	9.022
^{14}N(n,t)^{12}C*	-8.4540	9.063
^{14}N(n,2α)^{7}Li	-8.8232	9.459
^{14}N(n,2α)^{7}Li*	-9.3008	9.97
^{14}N(n, 2n)^{13}N	-10.5535	11.31
^{14}N(n,np)^{13}C*	-10.640	11.40
^{14}N(n,nα)^{10}B	-11.6125	12.44
^{14}N(n,nα)^{10}B*	-12.331	13.21
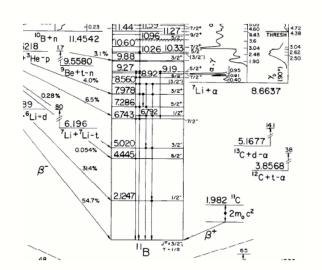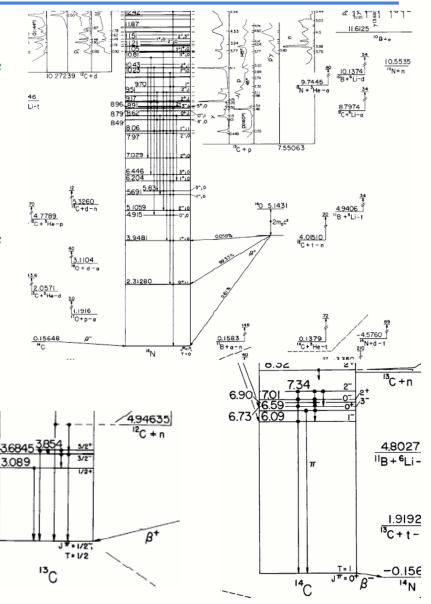
- ^{14}N abundance 99.634%
- γ production dominated by ^{14}N(n,n')^{14}N* and by ^{14}N(n,α)^{11}B* with some contribution from ^{14}N(n,p)^{14}C*, ^{14}N(n,t)^{12}C* and ^{14}N(n,d)^{13}C*
- ^{14}N(n,γ)^{15}N negligible: $\sigma_{(n,\gamma)}$(14 MeV)$\approx$10^{-5} b

γ production by n+^{14}N

- ^{14}N(n,n')^{14}N*
  - Excitation levels up to E_x=7.029 MeV contribute
- ^{14}N(n,α)^{11}B*
  - Excitation levels up to E_x=8.56 MeV contribute
- ^{14}N(n,p)^{14}C*
  - Excitation levels up to E_x=7.34 MeV contribute
- ^{15}N(n,d)^{14}C*
  - Excitation levels up to E_x=3.854 MeV contribute
- ^{14}N(n,t)^{12}C*
  - 4.44 MeV 2$^+$ level de-excitation
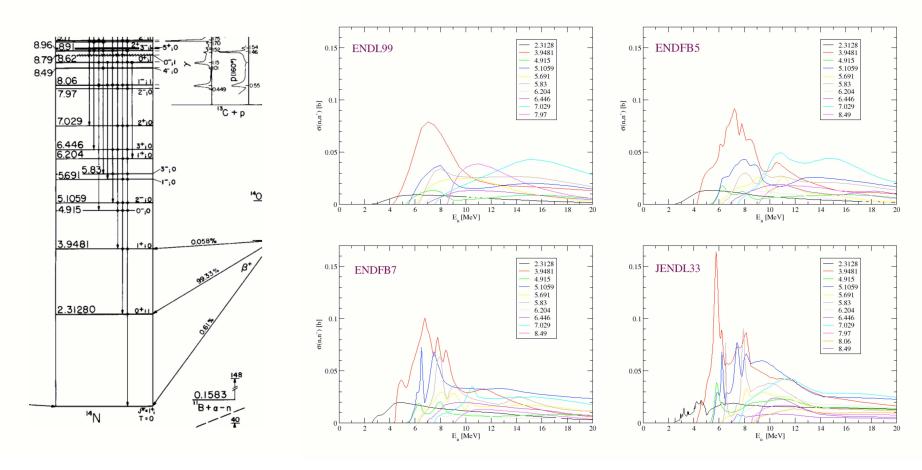
$^{14}N(n,n')^{14}N^*$
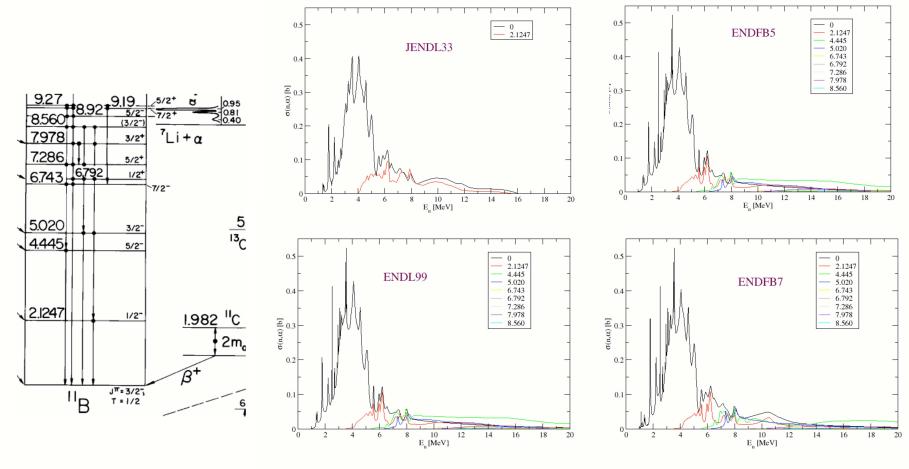
- (n,n') cross section dominated by 3.9481 MeV 1^+0, 5.1059 MeV 2^-0, 5.83 MeV 3^-0 levels, and above 9 MeV also by 7.029 MeV 2^+0 level.
- ENDL99 7.97 MeV cross section likely incorrect - above proton threshold
- Differences between ENDFB7 and JENDL33 significant

$^{14}N(n,\alpha)^{11}B$
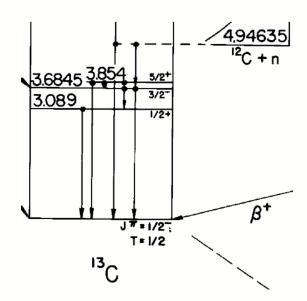
- Excitation of the 2.1247 1/2$^-$ level dominates the photo-production at energies up to about 8 MeV
- Excitation of the 4.445 5/2$^-$ level dominates at higher energies
- JENDL33: only gs and 2.1247 cross section given, errors in thresholds
- Both JENDL33 and ENDFB7(=6) reference Morgan, NSE 70, 163 (79) as an important source for evaluation. Still the cross sections differ somewhat.
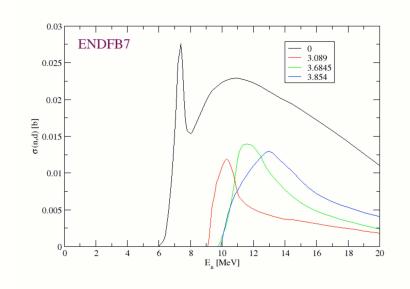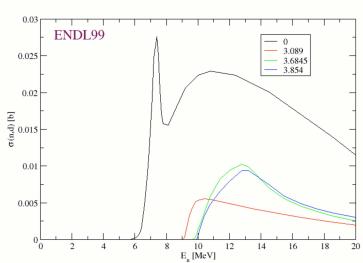
$^{14}N(n,d)^{13}C$

- Less important than (n,n') and (n,α)
- ENDL99 almost identical to ENDFB5
  - Error in $5/2^+$ energy
- Data missing in JENDL33
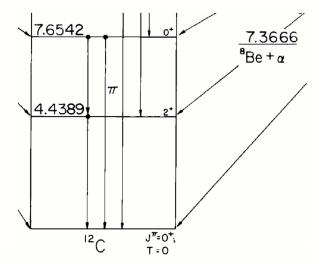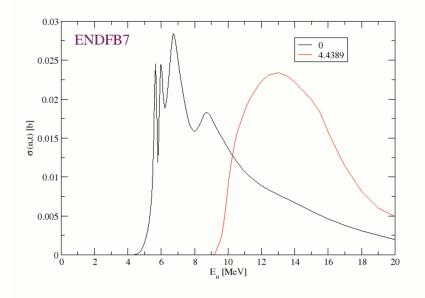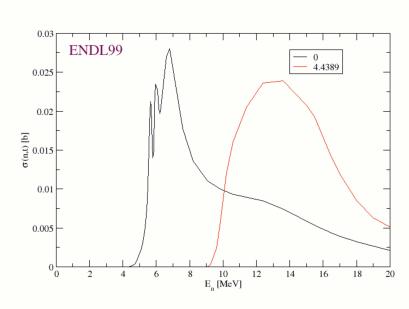
$^{14}N(n,t)^{12}C$

- (n,t) cross section for the 2^+0 excitation about 25 mb at 14 MeV
- ENDL99 almost identical to ENDFB5
- No data found in JENDL33
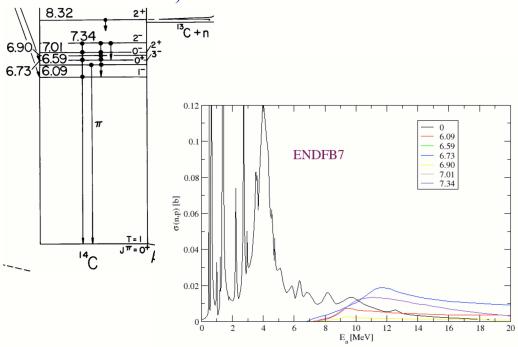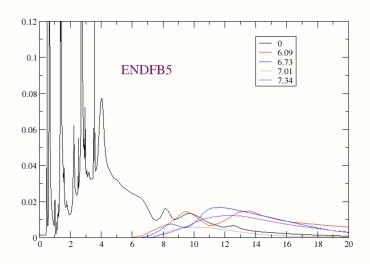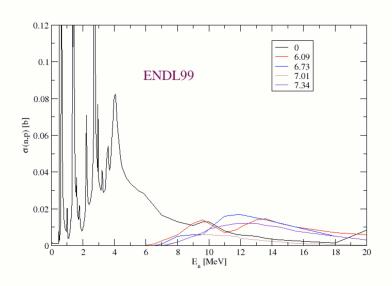
$^{14}N(n,p)^{14}C$

- The 6.09 1^-1, 6.73 3^-1, 7.01 2^+1 and 7.34 2^-1 levels contribute to gamma production
  - 3^- and 2^- levels dominant, cross section does not exceed 20 mb at 14 MeV
- ENDL99 similar to ENDFB5
  - Error in 2^+1 level energy (7.156 MeV vs. correct 7.01 MeV)
- 6.09 MeV data in Rogers, NSE 58, 298 (1975) in agreement with ENDFB7 (different from ENDL99, ENDFB5)
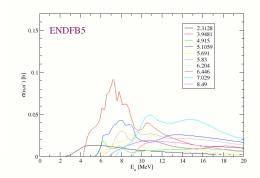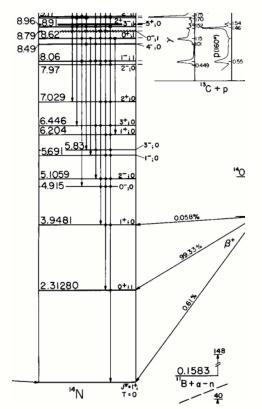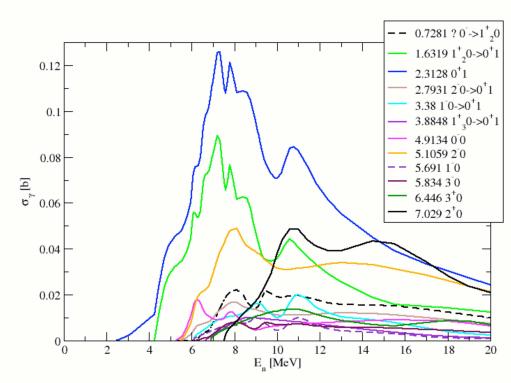
^{14}N(n,Xγ) evaluation in ENDFB5

- ## (n,Xγ) cross sections from ENDFB5

  - ### File yo00c55i000s003

  - ### Only transitions from (n,n')

  - ### Apparently an error in the $0^- \rightarrow 1^+_2$ energy

    - Likely $3^- \rightarrow 2^-$, error in threshold: 6.25, not 5.26

      - Rogers, NSE 58, 298 (1975)

Conclusions

- A lot of experimental data
- ENDFB7 and JENDL33 independent evaluations/calculations
  - JENDL33 uses Gnash code, in addition dwuck, casthy
  - Data references in general different for ENDFB7 and JENDL33
- ENDFB7 identical to ENDFB6
- ENDFB6 revises ENDFB5 by using
  - New experimental data
    - Some new experimental data private communications or unpublished reports
  - New R-matrix (below 2.5 MeV) and statistical model calculations (Gnash)
    - Hauser-Feschbach, pre-equilibrium, direct reaction theory
- ENDL99 similar to ENDFB5
- Only ENDFB5 contains gamma cross section file
- New data likely needed:
  - Ron Nelson, February 2007: "For 14N it appears that our measured cross sections are considerably larger (almost 2X in the 8 to 10 MeV neutron energy region) than the current ENDF values. At 14 MeV agreement is good."

$^{15}N(n,X\gamma)$

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9 February, 2007

n+^{15}N reactions for $E_n \leq 20$ MeV

Reaction	Q value [MeV]	Threshold Energy [MeV]
^{15}N(n,γ)^{16}N	+2.491	0
^{15}N(n,n)^{15}N	0	0
^{15}N(n,n')^{15}N*	-5.2702	5.62
^{15}N(n,α)^{12}B	-7.623	8.14
^{15}N(n,d)^{14}C	-7.983	8.52
^{15}N(n,α)^{12}B*	-5.3046	9.15
^{15}N(n, p)^{15}C	-9.989	9.59
^{15}N(n, p)^{15}C*	-9.729	10.38
^{15}N(n,t)^{13}C	-9.902	10.57
^{15}N(n, np)^{14}C	-10.274	10.96
^{15}N(n, 2n)^{14}N	-10.833	11.56
^{15}N(n,nα)^{11}B	-10.992	11.72
^{15}N(n,t)^{13}C*	-12.991	13.86
^{15}N(n,nα)^{11}B*	-13.116	13.99
^{15}N(n, 2n)^{14}N*	-13.146	14.02
^{15}N(n,d)^{14}C*	-14.073	15.01
^{15}N(n,np)^{14}C*	-16.364	17.46
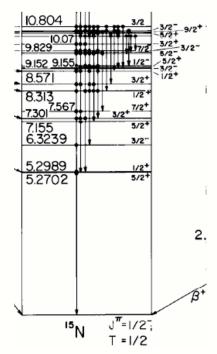
- ^{15}N abundance 0.366% (^{14}N 99.634%)
- γ production dominated by ^{15}N(n,n')^{15}N* with some contribution from ^{15}N(n,p)^{15}C*
- ^{15}N(n,γ)^{16}N negligible: $\sigma_{(n,\gamma)}$(14 MeV)≈10^{-5} b
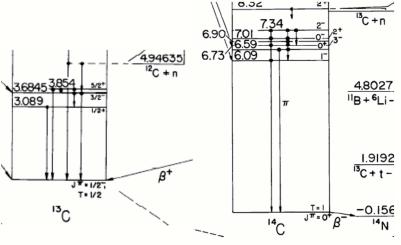
γ production by n+^{15}N

- ^{15}N(n,n')^{15}N*
  - 12 γ rays considered in ENDL99
  - 8 γ rays measured by Ron Nelson
  - 5.299 MeV, 6.324 MeV, 1.8848 MeV and 2.2968 MeV the most significant
  - Levels above E_x=10.8 MeV in ^{15}N decay by particle emission
- ^{15}N(n,p)^{15}C*
  - 1 γ ray (0.74 MeV) observed by Ron Nelson
- γ rays from other reactions considered in ENDL99
  - ^{15}N(n,α)^{12}B* (5 γ rays)
  - ^{15}N(n,t)^{13}C* (2 γ rays)
  - ^{15}N(n,d)^{14}C* (2 γ rays)
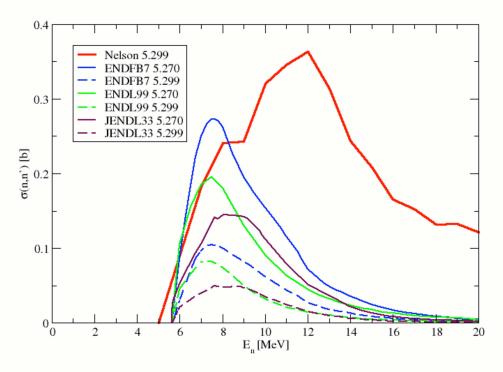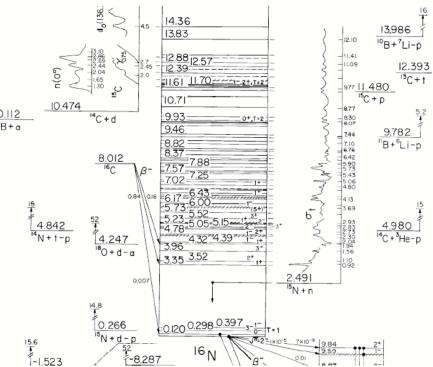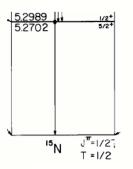
$^{15}N(n,n')^{15}N^*(5.2989)$

- A=16,17 TUNL evaluation, Nucl. Phys. **A564** (1993) 1
  - n+^{15}N 1/2$^-$(gs) ↔ 1/2$^+$(5.2989) cross section not shown
- Data evaluations
  - JENDL33
  - ENDL99
  - ENDFB5 identical to ENDL99
  - ENDFB6 identical to ENDFB7
  - New measurement by Ron Nelson
- Evaluations from modeling

Legend:
- Nelson 5.299
- ENDFB7 5.270
- ENDFB7 5.299
- ENDL99 5.270
- ENDL99 5.299
- JENDL33 5.270
- JENDL33 5.299

$\sigma(n,n')$ [b] vs E_n [MeV]

The 5/2$^+$ (5.270 MeV) cross section larger than the 1/2$^+$(5.299 MeV) one in evaluations

5.270 MeV is M2 transition
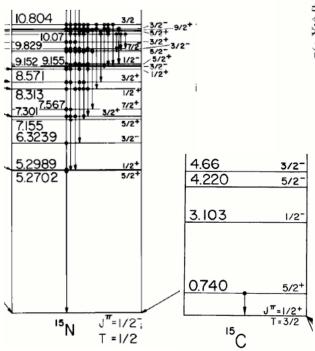
5.299 MeV is E1 transition
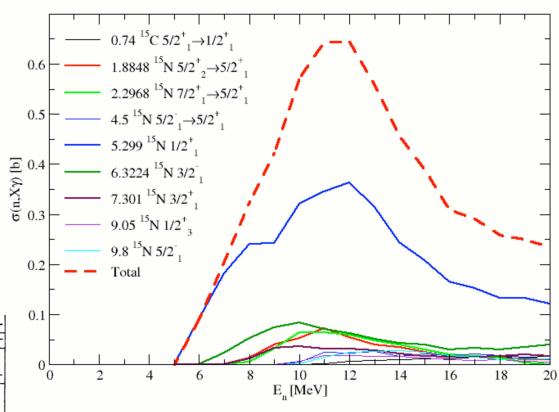
Nelson observes 5.299 MeV γ

^{15}N(n,Xγ) mesurement by R. Nelson

- 5.299 MeV and 6.322 MeV dominant

- Two transitions to $5/2^+_1$
  - No transition from $5/2^+_1$ to gs reported
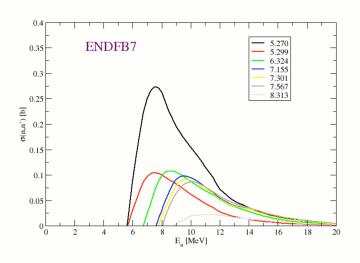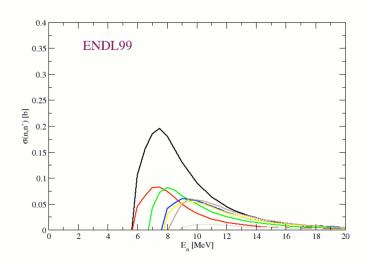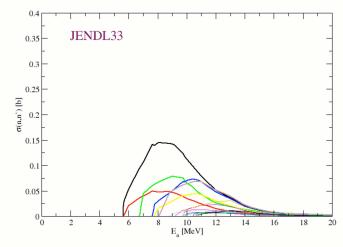
- (n,n') cross sections from ENDL99, EDEFB7, JENDL33
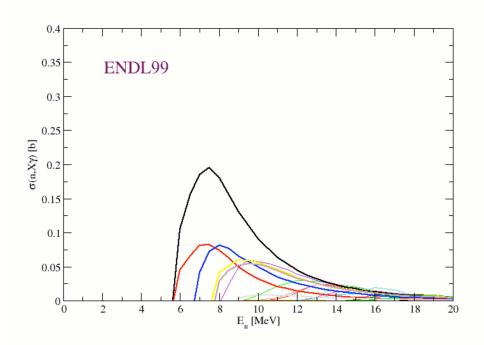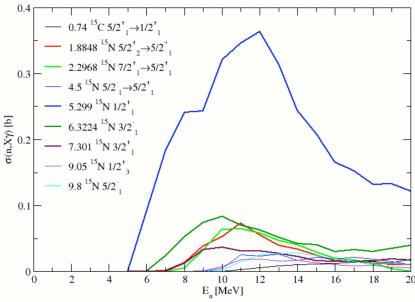
$^{15}N(n,X\gamma)$ evaluations

- (n,Xγ) cross sections from ENDL99 and Nelson's measurement

^{15}N(n,Xγ) evaluations

- **All databases contain**
  - (n,n') cross section files yo00c11i000s001 and yo00c11i000s000
  - Cross sections files yo00cxyi000s000 with xy=12,20,26,40,41,42,45
- **ENDL99 also contains**
  - (n,Xγ) cross section file yo00c55i000s003
    - Possible errors to check:
      - Threshold energy of 1.674 MeV (^{12}B 2$^-$ E_t=9.91 rather than 9.22 MeV)
      - Threshold energy of 3.684 MeV (^{13}C 3/2$^-$ E_t=14.492 rather than 14.0 MeV)
- **ENDEFB7 also contains**
  - (n, γ) cross section file yo00c46i000s000
- **ENDFB5 also contains**
  - yo00cxyi000s001 with xy=40,41,42,45
  - yo00c55i000s000
- **JENDL33 also contains**
  - yo00c46i000s000
  - yo00c55i000s000

Conclusions

- Due to lack of experimental data evaluations based on calculations
  - Optical model, R-matrix, statistical models
- ENDFB7 and JENDL33 independent evaluations/calculations
- ENDFB7 identical to ENDFB6
- ENDFB6 revises ENDFB5 by using
  - improved optical model parameters
  - updated level schemes
  - improved version of GNASH
  - better treatment of level density parameters
- ENDL99 similar as ENDFB5
  - Question: Why 5.299 (5.270) MeV (n,n') cross section (c11) the same as the 5.299 (5.270) MeV γ cross section (c55)?
- New measurement by R. Nelson differs from evaluations
  - Results preliminary, more analysis needed
- Likely the evaluations unreliable
- Some issues still need clarification
  - Decay of $5/2^+_1$ vs. $1/2^+_1$

$^{16}O(n,X\gamma)$
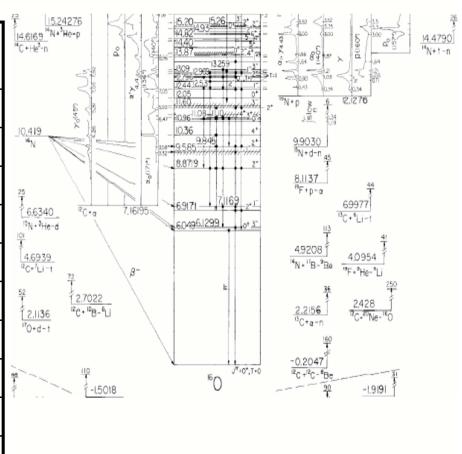
Petr Navratil

Lawrence Livermore National Laboratory*

12 January, 2007

n+^{16}O reactions for $E_n \leq 20$ MeV

Reaction	Q value [MeV]	Threshold Energy [MeV]
^{16}O(n,γ)^{17}O	+4.1436	0
^{16}O(n,n)^{16}O	0	0
^{16}O(n,α)^{13}C	-2.2156	2.354
^{16}O(n,α)^{13}C*	-5.3046	5.636
^{16}O(n,n')^{16}O	-6.1299	6.512
^{16}O(n,nα)^{12}C	-7.162	7.610
^{16}O(n, p)^{16}N	-9.6364	10.239
^{16}O(n,d)^{15}N	-9.903	10.521
^{16}O(n,t)^{14}N	-14.479	15.384
^{16}O(n,2n)^{15}O	-15.663	16.642
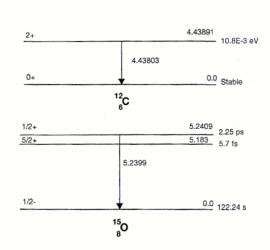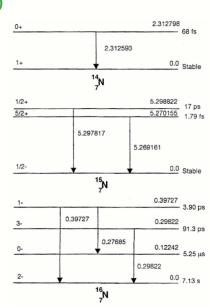
- γ production dominated by ^{16}O(n,n')^{16}O and ^{16}O(n,α)^{13}C*
  - 16 γ rays observed from these two reactions
  - Other 8 γ rays observed from other reactions shown in the table
- ^{16}O(n,γ)^{17}O negligible
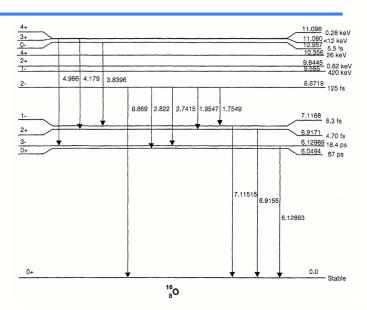
γ production by n+^{16}O
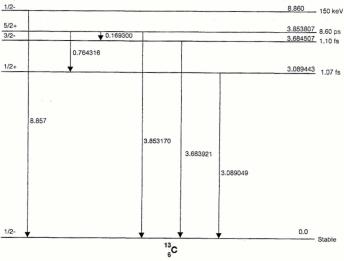
- ^{16}O(n,n')^{16}O
  - 11 γ rays observed
  - 6.13 MeV, 6.92 MeV and 7.12 MeV the most significant
  - Levels above E_x=11.1 MeV in ^{16}O decay by α emission
- ^{16}O(n,α)^{13}C*
  - 6 γ rays observed
- Other reactions shown in the table
  - (n,p), (n,d), (n,t), (n,2n)
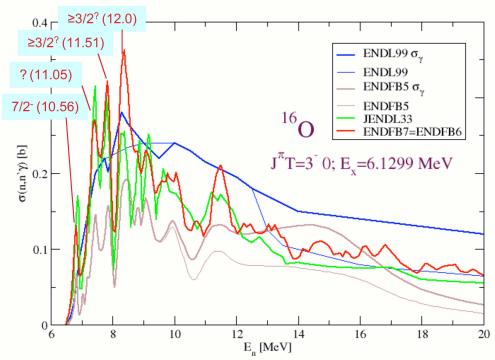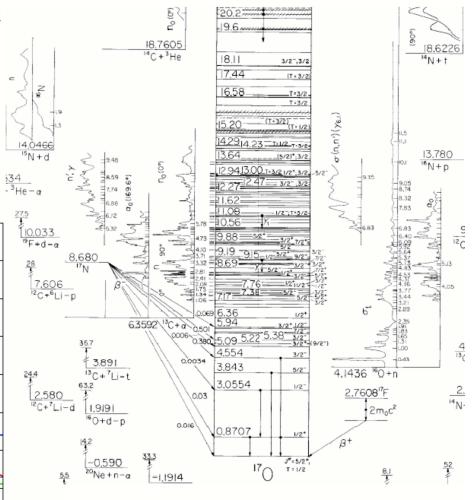
$^{16}O(n,n')^{16}O*(6.1299)$
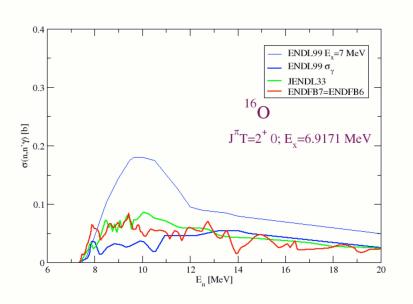
- *A*=16,17 TUNL evaluation, Nucl. Phys. **A564** (1993) 1
- Data evaluations
  - JENDL33
  - ENDL99
  - ENDFB5
  - ENDFB6 & ENDFB7
- Peaks correspond to ^{17}O resonances
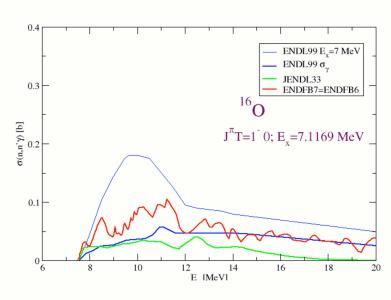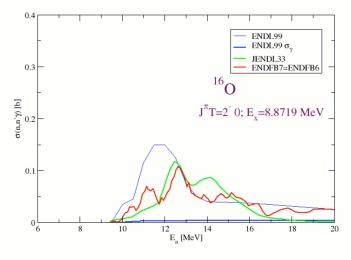
^{16}O(n,n')^{16}O*(E_x>6.13 MeV)
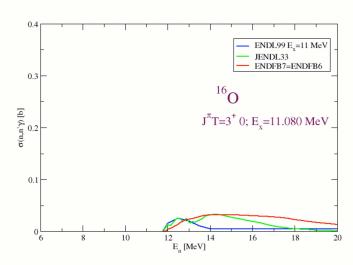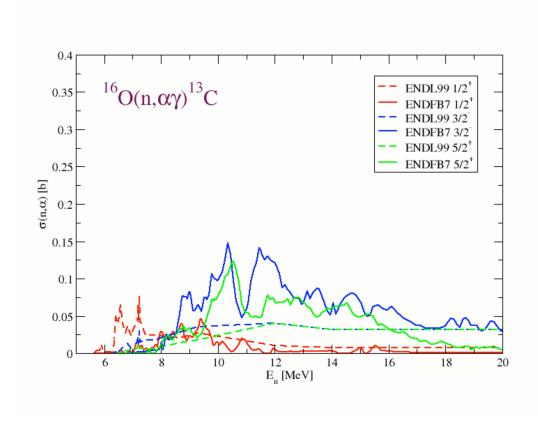
- 2$^-$ and 3$^+$ states decay by a sequence of 2 γ-rays
- 0$^+$ state cross section very small

$^{16}O(n,\alpha)^{13}C^*$

- Transitions from $3/2^-$ (3.685 MeV) and $5/2^+$ (3.854 MeV) significant

$^{16}O(n,X\gamma)$ evaluations
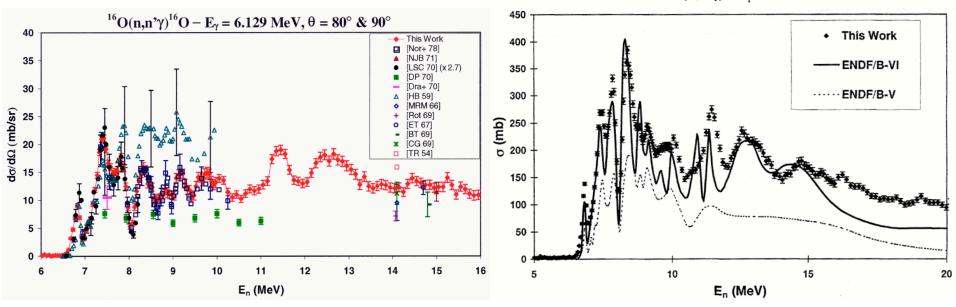
- **All databases contain**
  - (n,n') cross section files yo00c11i000s001
- **ENDFB5 contains**
  - (n,α) cross section file yo00c45i000s001
  - (n,Xγ) cross section file yo00c55i000s003
- **ENDL99 contains**
  - yo00c55i000s003, yo00c45i000s001, yo00c11i000s000
- **ENDFB7 & ENDFB6 contain**
  - yo00c11i000s000, yo00c45i000s000, yo00c45i000s001

ENDFB7 ^{16}O(n,Xγ) evaluation

- Based almost entirely on a new experiment performed at the WNR at LANL

  - R.O. Nelson and A. Michaudon, High-Resolution Cross Section Measurement of Photon Production from ^{16}O(n,Xγ) Reaction for Neutron Energies Between 4 and 200 MeV, LA-UR-99-4170 (1999)

    - High-energy pulsed neutron source

      - 800 MeV pulsed protons from the LANSCE accelerator on tungsten target

    - BeO target

    - 2 Ge γ detectors at 7 angles

    - 23 γ-rays from ^{16}O(n,Xγ) measured

    - Data compared to previous measurements

^{16}O(n,n'γ)^{16}O − E$_γ$ = 6.129 MeV, θ = 80° & 90°

^{16}O(n,n'γ) − E$_γ$ = 6.129 MeV

Conclusions

- The ENDFB7 evaluation based on a new measurement performed at WNR
  - Translation appears incomplete
    - No γ-ray cross sections
    - No data on $^{16}O(n,n\alpha)^{12}C^*$
- ENDL99 appears to have incomplete data
  - some resonances missing
  - Discrepancies found, e.g.
    - $\sigma_\gamma > \sigma(n,n')$ for 6.13 MeV state at E_n=8 MeV
    - $2^-(8.87) \rightarrow 3^-(6.13)$ not taken into account properly as for $\sigma_{\gamma(6.13)} = \sigma(n,n')_{6.13}$ for 9.4 MeV$<E_n<$ 11.8 MeV
  - γ-ray cross sections in c55 files
- ENDFB5 evaluation based on older data
  - LLNL measurement by E. Goldberg et al., NSE **105**, 319 (1990):
    - ENDBF5 $^{16}O(n,X\gamma)$ cross section at 14 MeV too low
    - ENDFB7 cross section higher (2 times for 6.13 MeV γ ray)

^{19}F(n,Xγ)
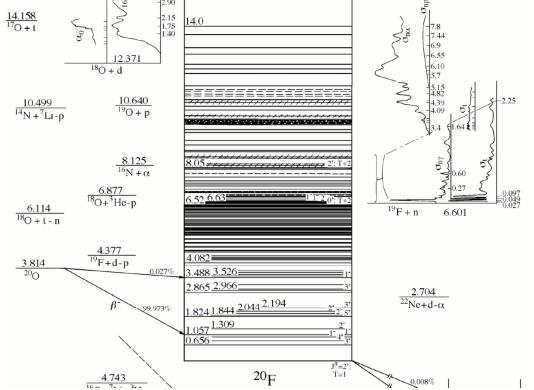
Petr Navratil

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25 May, 2007
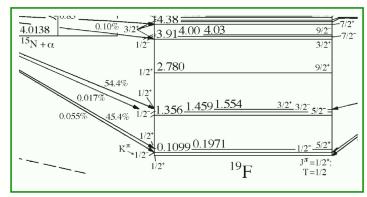
n+^{19}F reactions for $E_n \leq 20$ MeV

Reaction	Q value [MeV]	Threshold Energy [MeV]
^{19}F(n,γ)^{20}F	+6.601	0
^{19}F(n,n)^{19}F	0	0
^{19}F(n,n')^{19}F*	-0.1099	0.116
^{19}F(n,α)^{16}N	-1.524	1.604
^{19}F(n,α)^{16}N*	-1.644	1.731
^{19}F(n,nα)^{15}N	-4.0138	4.225
^{19}F(n,p)^{19}O	-4.4039	4.252
^{19}F(n,p)^{19}O*	-4.4999	4.737
^{19}F(n,d)^{18}O	-5.7697	6.073
^{19}F(n,t)^{17}O	-7.557	7.955
^{19}F(n,d)^{18}O*	-7.7518	8.16
^{19}F(n,np)^{18}O	-7.9942	8.42
^{19}F(n,t)^{17}O*	-8.4277	8.871
^{19}F(n,nα)^{15}N*	-9.284	9.773
^{19}F(n,np)^{18}O*	-9.9763	10.501
^{19}F(n,2n)^{18}F	-10.432	10.987
^{19}F(n,2n)^{18}F*	-11.3692	11.968
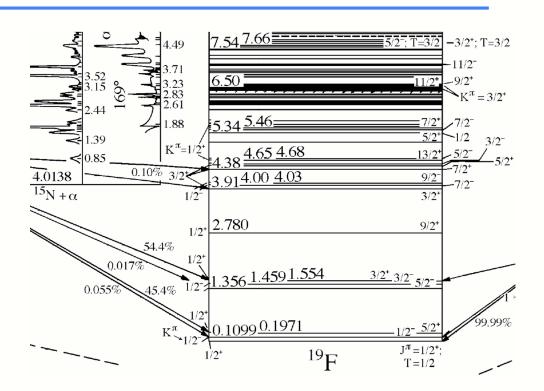
- ^{19}F abundance 100%
- γ production from ^{19}F(n,n')^{19}F*
- Significant contribution from ^{19}F(n,α)^{16}N*
- ^{19}F(n,γ)^{20}F negligible: $\sigma_{(n,\gamma)}$(14 MeV)$\approx$0
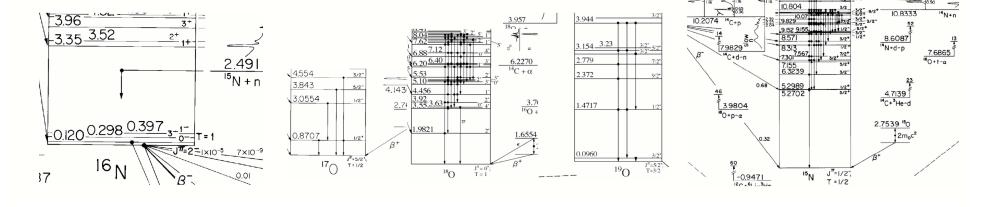
γ production by n+¹⁹F

- ¹⁹F(n,n')¹⁹F*
  - Levels up to E_x=5.6 MeV contribute
- ¹⁹F(n,α)¹⁶N*
  - Levels up to E_x=2.5 MeV contribute
- ¹⁹F(n,p)¹⁹O*
  - Levels up to E_x=3.94 MeV may contribute
- ¹⁹F(n,d)¹⁸O*
  - Levels up to E_x=6.4 MeV may contribute
- ¹⁹F(n,t)¹⁷O*
  - Levels up to E_x=4.6 MeV may contribute
- ¹⁹F(n,nα)¹⁵N*
  - Levels up to E_x=10 MeV may contribute
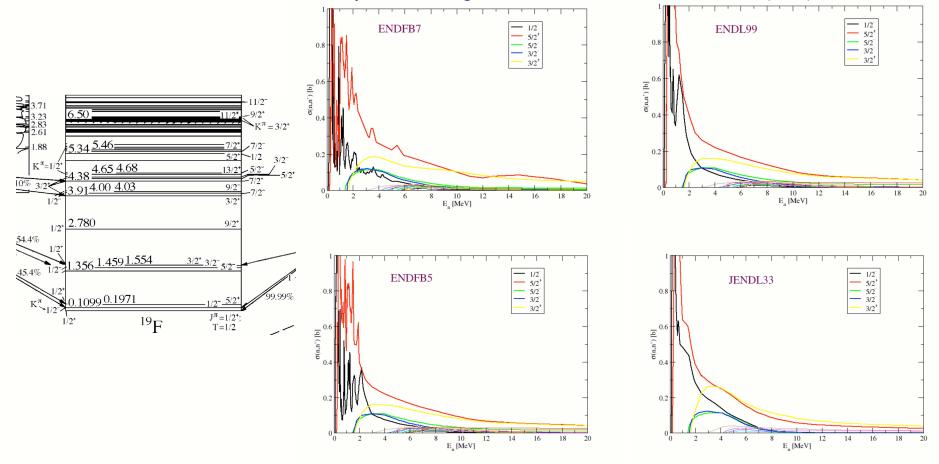
$^{19}F(n,n')^{19}F^*$
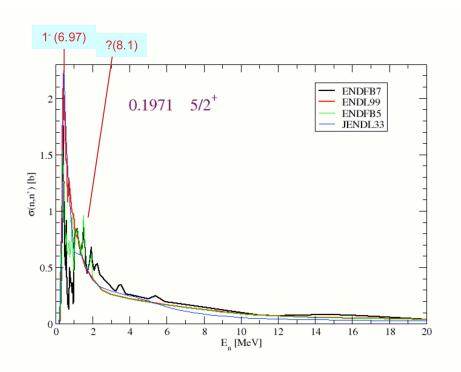
- (n,n') cross section dominated by 0.1099 MeV $1/2^-$ and 0.1971 MeV $5/2^+$ levels and above 3 MeV also by 1.554 MeV $3/2^+$
  - ENDL99: error in $5/2^-_1$ state excitation energy
- Measurement by Day *at al.*, PR 117, 1330 (1960) at 2.56 MeV
  - $1/2^-$ 0.11 MeV cross section from angular distribution: 0.18 b
- ENDFB evaluation based mostly on G.L. Morgan and J.K. Dickens, ORNL/TM-4823 (1974).
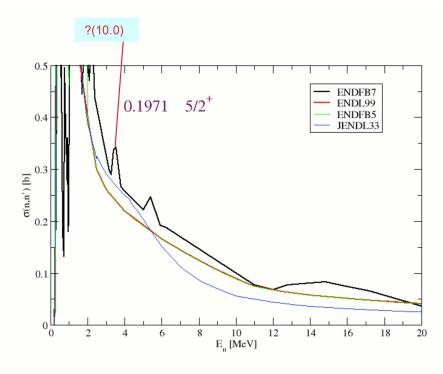
$^{19}F(n,n')^{19}F*(0.1971)$

- ENDL99 and JENDL33 averages the peaks at 1 MeV
- Above 3 MeV ENDF and ENDL evaluations similar, JENDL lower (from 6 MeV on)
- Low-lying resonances can be identified as ^{20}F states
- Measurement by Day *at al.*, PR 117, 1330 (1960) at 2.56 MeV
  - Cross section from angular distribution: 0.53 b
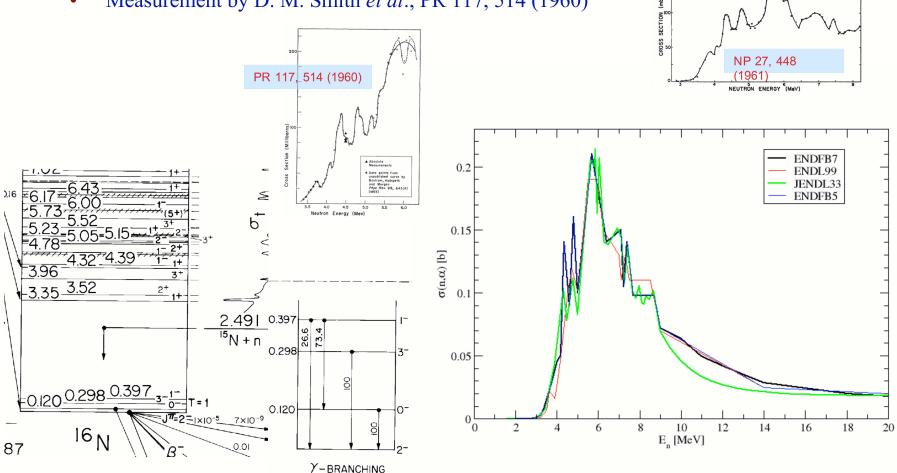
$^{19}F(n,\alpha)^{16}N$
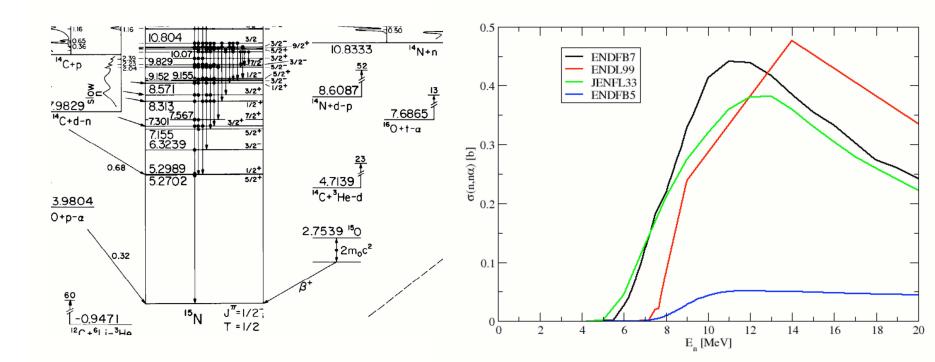
- ^{16}N levels small excitation energy: contribution to gamma production
- All evaluations in a good agreement up to 9 MeV, above that JENDL33 lower
- Measurement by E. A. Davis *et al.*, NP **27**, 448 (1961)
- Measurement by D. M. Smith *et al.*, PR 117, 514 (1960)

$^{19}F(n,n\alpha)^{15}N$
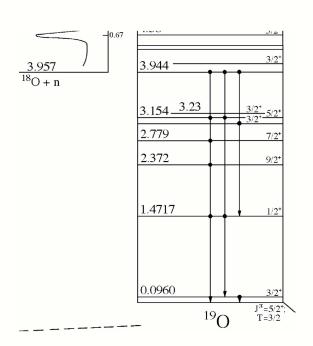
- Large cross section, above 10 MeV should contribute to gamma production
- Significant differences among evaluations
- Based on calculations
  - ENDFB7: TNG code
  - JENDL33: Sincros-II code system
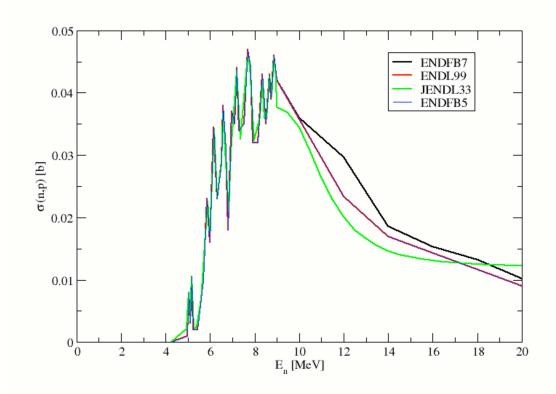
$^{19}F(n,p)^{19}O$

- Cross sections very small
- Good agreement among evaluations
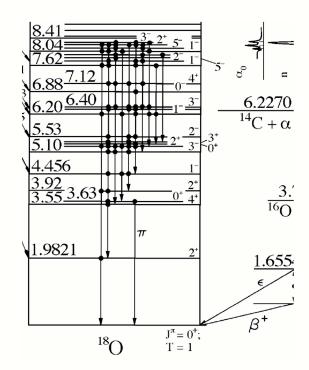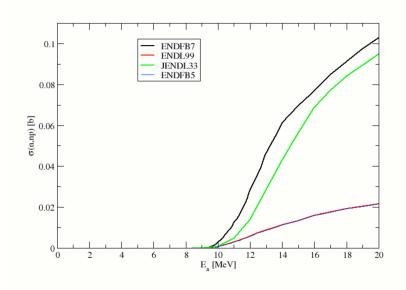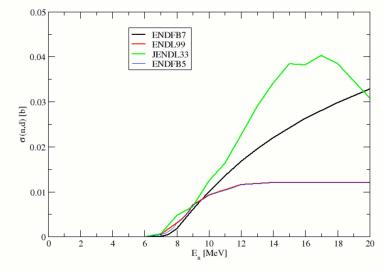
$^{19}F(n,d)^{18}O$ & $^{19}F(n,np)^{18}O$

- Cross sections non-negligible
- Above 10 MeV should contribute to gamma production
- ENDFB7: Experimental reference M. Fazio *et al.*, **NPA** 111, 225 (1968)
  - Measurement at 14 MeV
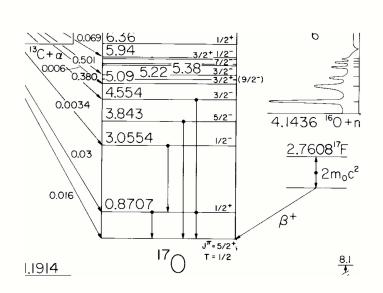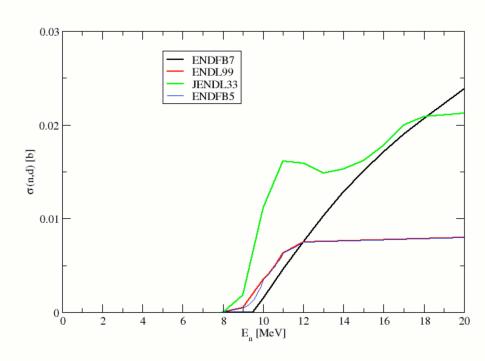
- Cross sections very small
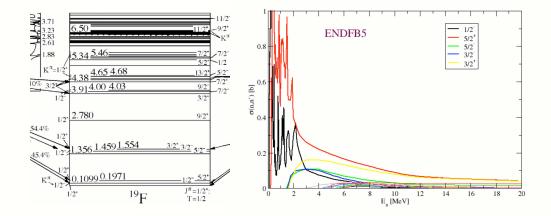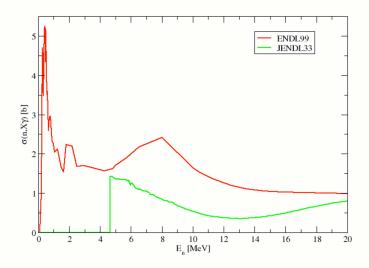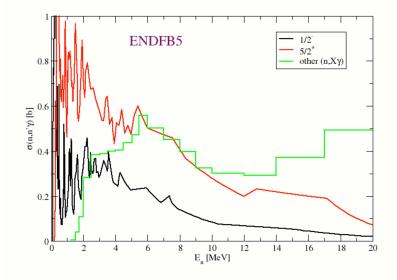
^{19}F(n,Xγ)

- Only ENDFB5 contains gamma production cross sections for discreet levels
- Gamma rays from (n,n') only
- Cross section in ENDL99 much larger than in ENDFB5 or JENDL33 and also larger compared to expected values from (n,n')

$^{19}F(n,X\gamma)$ evaluations

- **All databases contain**
  - (n,n') cross section files yo00c11i000s001
  - Cross sections files yo00cxyi000s000 with xy=12(n,2n), 20(n,np), 26 (n,nα), 40(n,p), 41(n,d), 42(n,t), 45 (n,α), 46(n, γ)
- **ENDL99 also contains**
  - Cross section file yo00c55i000s000: (n,Xγ)
- **ENDFB5 also contains**
  - Cross section file yo00c55i000s000: (n,Xγ)
  - Cross section file yo00c55i000s003: (n,n'γ)
- **JENDL33 also contains**
  - Cross section file yo00c55i000s000: (n,Xγ)

Conclusions

- Some experimental data published as reports
- ENDFB7
  - SAMMY R-matrix calculations up to 1 MeV
  - Higher energies: TNG statistical and precompound theory code
- ENDL99 needs to be updated
- All evaluations in reasonable agreement for (n,n'), (n,α), (n,p) cros sections
- Significant (n,nα) cross section
  - Agreement between ENDFB7 and JENDL33
- Gamma production data missing in the present data sets
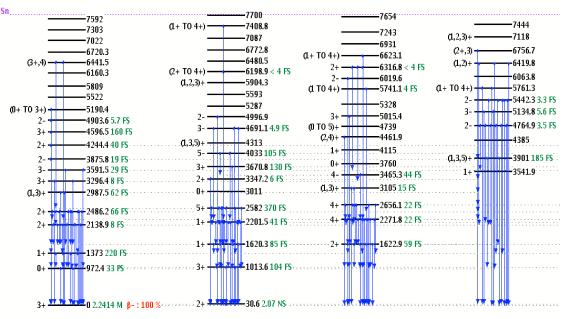- Presently, the ENDFB7 appears the most solid

$^{27}Al(n,X\gamma)$

Petr Navratil

Lawrence Livermore National Laboratory*

8 June, 2007
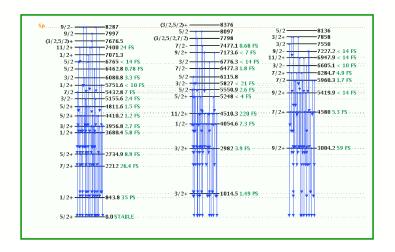
n+^{27}Al reactions for $E_n \le 20$ MeV

Reaction	Q value [MeV]	Threshold Energy [MeV]
^{27}Al(n,γ)^{28}Al	+7.725	0
^{27}Al(n,n)^{27}Al	0	0
^{27}Al(n,n')^{27}Al*	-0.844	0.875
^{27}Al(n,p)^{27}Si	-1.8285	1.897
^{27}Al(n,p)^{27}Si*	-2.609	2.706
^{27}Al(n,α)^{24}Na	-3.130	3.247
^{27}Al(n,α)^{24}Na*	-3.602	3.736
^{27}Al(n,d)^{26}Si	-6.0475	6.274
^{27}Al(n,d)^{26}Si*	-7.8434	8.134
^{27}Al(n,np)^{26}Si	-8.272	8.581
^{27}Al(n,np)^{26}Si*	-10.068	10.441
^{27}Al(n,nα)^{23}Na	-10.09	10.467
^{27}Al(n,nα)^{23}Na*	-10.53	10.92
^{27}Al(n,t)^{25}Si	-10.883	11.29
^{27}Al(n,2n)^{26}Al	-13.058	13.546

- ^{27}Al abundance 100%
- γ production from ^{27}Al(n,n')^{27}Al*
- Contribution from ^{27}Al(n,np)^{26}Si*
- ^{27}Al(n,γ)^{28}Al negligible: $\sigma_{(n,\gamma)}$(14 MeV) $\approx$ 6x10^{-4} b
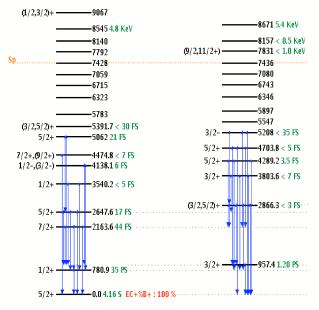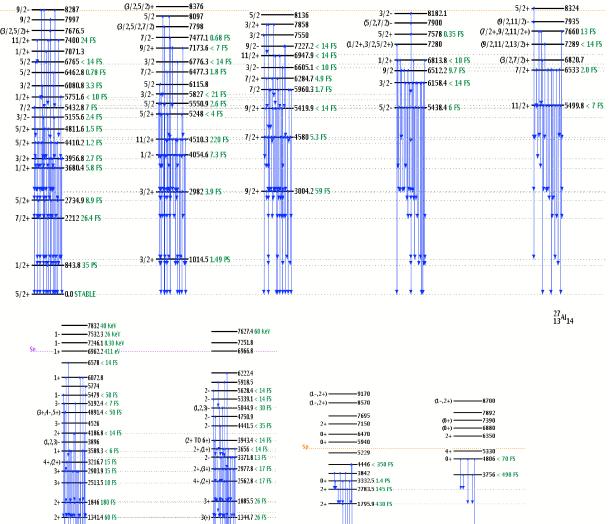
γ production by n+²⁷Al

- ²⁷Al(n,n')²⁷Al*
  - Levels up to E_x=8.4 MeV contribute
- ²⁷Al(n,p)²⁷Si*
  - Levels up to E_x=7.4 MeV contribute
- ²⁷Al(n,α)²⁴Na*
  - Levels up to E_x=7.0 MeV contribute
- ²⁷Al(n,np)²⁶Si*
  - Levels up to E_x=5.3 MeV contribute
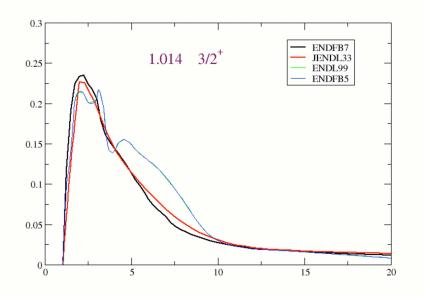- ²⁷Al(n,nα)²³Na*
  - Levels up to E_x=9 MeV contribute
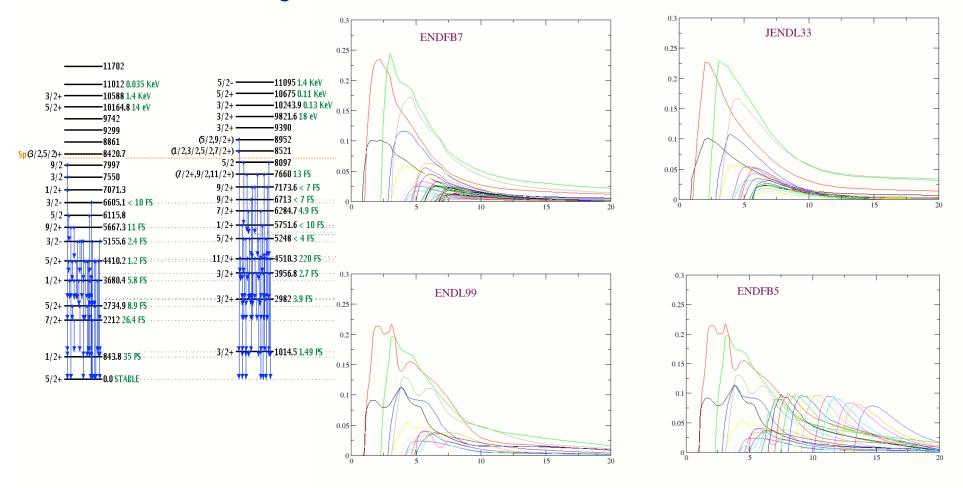
$^{27}Al(n,n')^{27}Al^*$

- Experiments at ORNL by Dickens *et al.*, published in reports
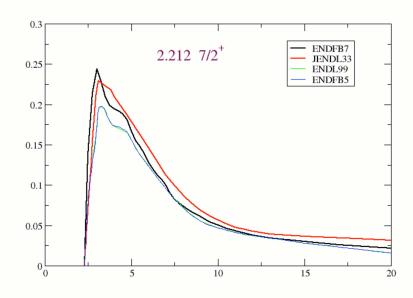 - ORNL-TM-3284 (1971); ORNL-TM-4232 (1973)
- Reasonable agreement between ENDFB7 and JENDL33

²⁷Al(n,n')²⁷Al*(1.014,2.212)

- ENDL99 and ENDFB5 almost identical
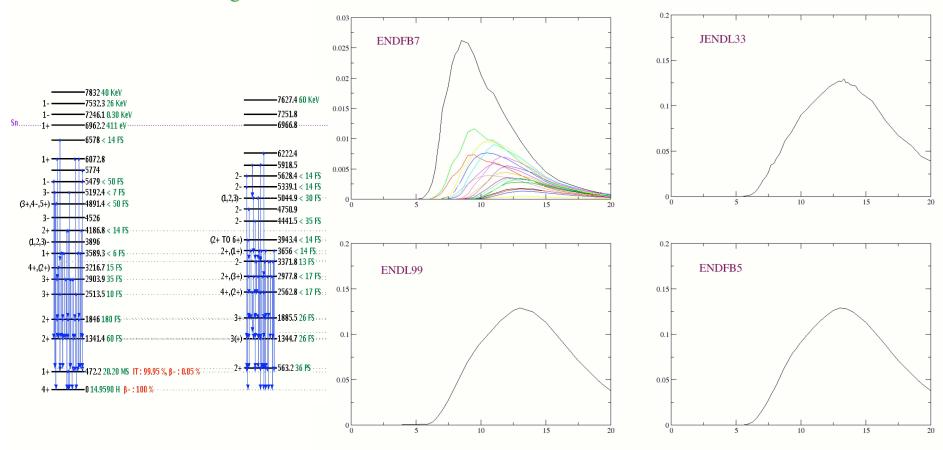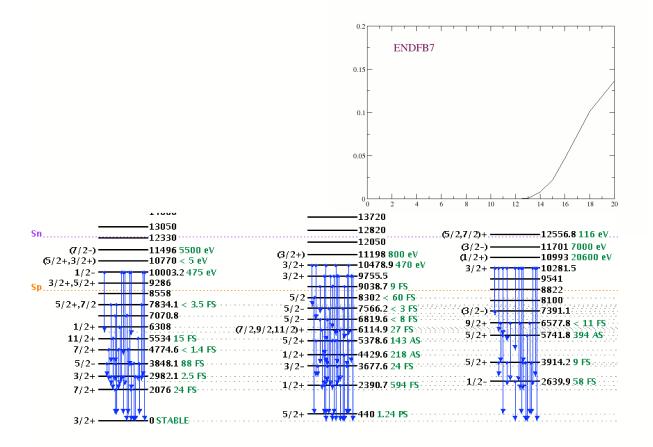- Good agreement between ENDFB7 and JENDL33

^{27}Al(n,α)^{24}Na

- **ENDFB7 - cross sections for single levels**
  - *About 10 times smaller than (n,n')*
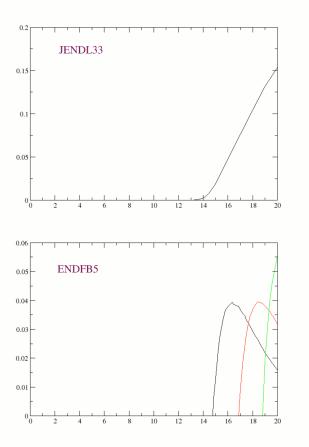- **Other evaluations total (n,α) cross sections**
  - *Good agreement*

$^{27}Al(n,n\alpha)^{23}Na$

- High threshold but cross section large at 20 MeV
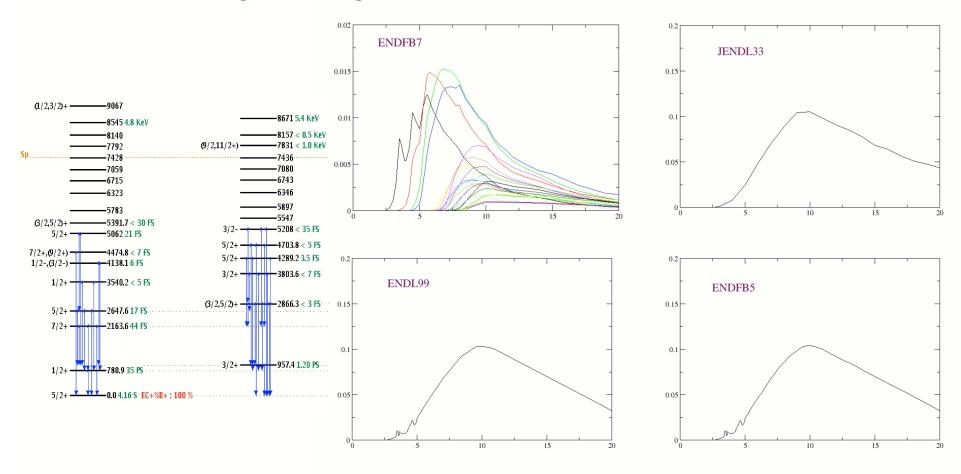- No data in ENDL99
- Good agreement between ENDFB7 and JENDL33
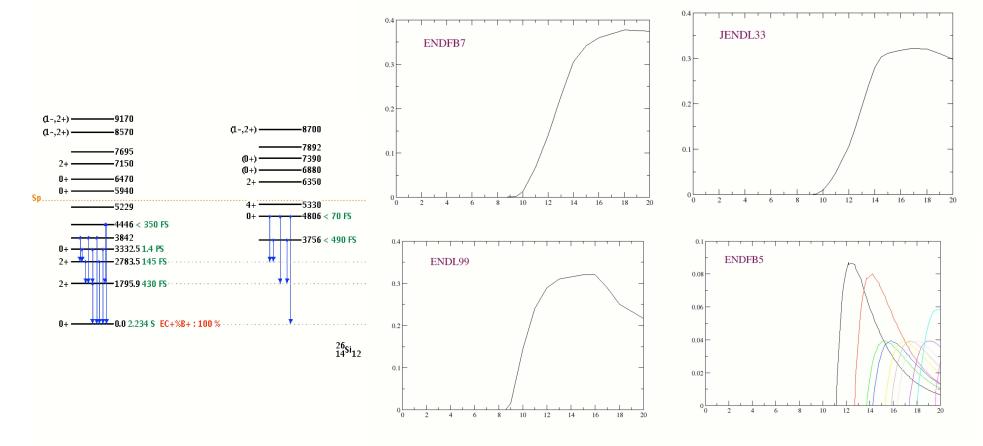
$^{27}Al(n,p)^{27}Si$

- **ENDFB7 - cross sections for single levels**
  - About order of magnitude smaller than (n,n')
- **Other evaluations total (n,p) cross sections**
  - Good agreement among evaluations
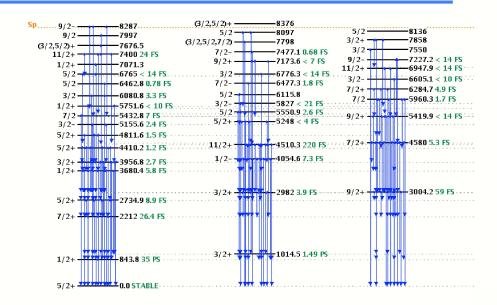
^{27}Al(n,np)^{26}Si

- Very large cross section at 14 MeV (~ 300 mb)
- Threshold for gamma-production at 10.4 MeV
  - Should produce gamma-ray at energies > 11 MeV
- ENDFB7, JENDL33 and ENDL99 evaluations in a reasonable agreement
  - Only total (n,np) included
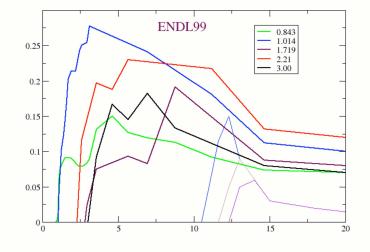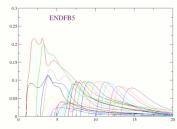- ENDFB5 cross section in bins
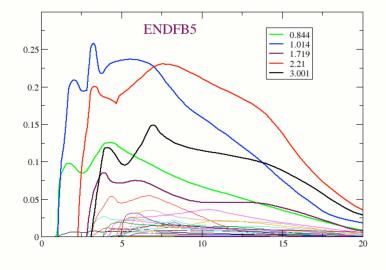
^{27}Al(n,Xγ)

- Evaluations in ENDFB5 and ENDL99
  - yo00C55i000s003 files
- Gamma-rays from (n,n')
- Strongest transitions:
  - 0.844 $1/2^+ \rightarrow$ gs
  - 1.014 $3/2^+ \rightarrow$ gs
  - 1.719 $5/2^+ (2.735) \rightarrow 3/2^+ (1.014)$
  - 2.212 $7/2^+ \rightarrow$ gs
  - 3.001 $9/2^+ \rightarrow$ gs
- No gamma-rays from (n,np)

Conclusions

- Most experimental data published as reports
- ENDFB7
  - SAMMY R-matrix calculations for resonances up to 850 keV
  - Higher energies: Statistical and pre-compound theory, FKK/GNASH/GSCAN codes
- JENDL33
  - Sincros-II calculations, codes Casthy, Ecis, Jupitor
- ENDL99 needs to be updated
- All evaluations in reasonable agreement for (n,n'), (n,α), (n,p) cros sections
- Significant (n,np) cross section
  - Agreement between ENDFB7 and JENDL33
- (n,nα) cross sections missing in ENDL99
  - Agreement between ENDFB7 and JENDL33
- Gamma production evaluation in ENDFB5 and ENDL99
  - Gamma rays from (n,n') only
- Presently, the ENDFB7 appears the most solid